Napredna metoda energijske analize za optimalno rješenje pri obnovi zgrada

Stjelja, Davor

UNIVERSITY OF ZAGREB
FACULTY OF MECHANICAL ENGINEERING
AND NAVAL ARCHITECTURE

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Davor Stjelja

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ADVANCED ENERGY ANALYSIS METHOD FOR OPTIMAL BUILDING RETROFIT DESIGN

Supervisor: Prof. dr. sc. Igor Balen, dipl. ing.

Student: Davor Stjelja

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NAPREDNA METODA ENERGIJSKE ANALIZE ZA OPTIMALNO RJEŠENJE PRI OBNOVI ZGRADA

Mentor: Student:

Prof. dr. sc. Igor Balen, dipl. ing. Davor Stjelja

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Datum	Prilog
Klasa:	
Ur.broj:	

DIPLOMSKI ZADATAK

Student: **DAVOR STJELJA** Mat. br.: 0035181612

Naslov rada na hrvatskom jeziku: **NAPREDNA METODA ENERGIJSKE ANALIZE ZA OPTIMALNO RJEŠENJE PRI OBNOVI ZGRADA**

Naslov rada na engleskom jeziku: **ADVANCED ENERGY ANALYSIS METHOD FOR OPTIMAL BUILDING RETROFIT DESIGN**

Opis zadatka:
In this thesis it is necessary to develop and describe a method for the selection of an optimal design solution for the building retrofit based on Building Energy Simulation (BES). The example for the method used in the thesis will be a high school building located in Helsinki, Finland. The work needs to include an overview of data availability and requirements for building energy modeling, as well as the description of current and advanced data collection methods. BES will be utilized throughout the process, from simplified to more complex simulations, depending on the level of detailed data currently available. An additional focus will be on the sensitivity analysis implementation, both in the phase of data collection and the phase of an optimal design solution selection. The selection of an optimal retrofit solution will be based on the analysis of different simulation cases, with the goal to decrease building energy needs. The optimal solution will be chosen taking into account energy performance indicators as well as economic indicators. The emphasis throughout the process should be on Building Information Modeling (BIM) based approach.

In the thesis it is necessary to complete the tasks outlined below:

- Give an overview of data availability and requirements for BES.
- Describe current and advanced data collection methods.
- Implement sensitivity analysis in decision making process and data collection.
- Create as-is BES model from simplified to more detailed stage.
- Simulate possible retrofit designs and select the optimal solution.
- Perform simple Life Cost Calculation (LCC).

It is advised to list references used in this work, as well as to acknowledge help and support possibly received during the course of this study.

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I hereby declare that this thesis is entirely the result of my own work and knowledge obtained during my studies and work on traineeship program, except where otherwise indicated. I have fully cited all used sources and I have only used the ones given in the list of references.

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Davor Stjelja, March 17th, 2016

CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

In this work advanced energy analysis method for optimal building retrofit design was developed and described. Method is based on Building Information Modelling (BIM) approach with the use of building energy simulations (BES) for the purpose of building retrofit feasibility and selection of optimal building retrofit solution.

First, description of BIM-based approach from the perspective of energy analysis throughout the life cycle of the building (from planning, through construction to building exploitation phase) was described. Afterwards, overview of necessary information for creating BES model and list of possible data providers was given.

After that followed the literature review of data collection methods, mostly methods for collection of data about geometry of the building and thermal properties of building envelope. Methods listed in this work are both usual data collection methods for energy analysis of a building and advanced methods still in research.

In this work sensitivity analysis was necessary for assessing the importance of input variables to BES in relation on output variable. To include this, overview of most common sensitivity analysis methods used in building energy analysis was given in this work. Sensitivity analysis method selected for this work is regression method.

Example of method for selecting the optimal retrofit solution of a building is given in this work. Two BES models were created for high school building located in Helsinki, Finland: simple model with approximated values and detailed model with acquired information of the building. Simple model was used for feasibility analysis of retrofitting the school building, while detailed model was used for selection of optimal retrofit solution. Finally, both of BES models were compared with their input and output variables from simulation.

Key words: building retrofit, energy analysis, building energy simulation, BIM, BES, data collection methods, sensitivity analysis

SAŽETAK

U ovom radu razvijena i opisana je napredna metoda energijske analize za optimalno rješenje pri obnovi zgrada. Metoda se bazira na Building Information Modelling (BIM) načinu rada uz korištenje energijskih simulacija za analizu isplativosti obnove pojedine zgrade i odabir optimalnog rješenja obnove.

Najprije je dan opis BIM načina rada sa aspekta energijske analize kroz čitav životni vijek projekta obnove (od faze planiranja, preko izgradnje do faze uporabe zgrade). Zatim je napravljen pregled potrebnih informacija za izradu modela za energijsku simulaciju zgrada, kao i pregled pružatelja potrebnih informacija.

Pregledom literature opisane su metode za prikupljanje podataka o zgradi, najvećim dijelom podacima o geometriji zgrade te termodinamičkih svojstvima njene ovojnice. Navedene su i uobičajene metode prikupljanja podataka kod energijske analize kao i napredne metode koje su još u fazi istraživanja.

Za ovu metodu potrebno je bilo koristiti analizu osjetljivosti ulaznih varijabli u simulaciju u ovisnosti o izlaznoj varijabli. Kako bi to bilo moguće napravljen je pregled najčešće korištenih metoda za analizu osjetljivosti u ovom području. Odabrana metoda analize osjetljivosti u ovom radu je metoda regresije.

U praktičnom dijelu rada prikazana je ideja metode za odabir optimalnog rješenja obnove zgrada. Zgrada srednje škole u Helsinkiju, Finskoj poslužila je kao primjer, napravljena su dva energijska modela: jednostavniji sa aproksimiranim informacijama, te detaljniji sa pribavljenim informacijama o zgradi. Jednostavniji model je poslužio za analizu isplativosti same obnove zgrade, a detaljniji za odabir optimalnog rješenja obnove zgrade. Konačno, uspoređena su oba modela s obzirom na njihove ulazne i izlazne varijable.

Ključne riječi: obnova zgrada, energijska analiza, energijske simulacije zgrada, BIM, BES, metode za prikupljanje podataka, analiza osjetljivosti

PROŠIRENI SAŽETAK (EXTENDED SUMMARY IN CROATIAN)

Ovaj rad podijeljen je na osam poglavlja. U prvom poglavlju, koje predstavlja uvod, dan je opis motivacije za ovaj rad. Motivacija ovog rada temelji se na činjenici kako u Europi veliki udio potrošnje energije kao i emisije ugljikovog dioksida dolazi iz sektora zgradarstva. Većina postojećih zgrada ne zadovoljava današnje kriterije gradnje u smislu energijske učinkovitosti. Trenutan udio zgrada u obnovi na razini EU iznosi 1 – 2 % godišnje, što je premalo za postizanje ciljeva koje je Europska Unija zadala. Cilj ovog rada je promijeniti proces obnove zgrada, od faze planiranja preko faze građenja do održavanja zgrada, da bi se povećao udio obnove zgrada u Europi, a time i smanjila potrošnja energije.

U drugom poglavlju govori se o Building Information Modelling (BIM) pristupu sa aspekta energijske analize. BIM se može shvatiti kao digitalni pristup planiranju zgrada, koji omogućuje lakšu i bržu suradnju između različitih struka (arhitektonske, građevinske, strojarske, itd.) i različitih strana (investitor, projektant, izvođač, itd.) u projektu. BIM se već uvelike koristi u svijetu, ali uglavnom za arhitektonske potrebe i uglavnom kod novih zgrada, dok se vrlo rijetko koristi za potrebe energijske analize zgrada, kao i u obnovi postojećih zgrada. Integracijom energijske analize i BIM načina rada može se lakše doći do zgrade s manjom potrebom za energijom jer se prije svake odluke provjerava njen utjecaj na potrošnju energije. Također energijske analizom se može i u fazi prije projektiranja obnove zgrade, analizirati potencijal određene zgrade za energetskom obnovom. Ideja je da se sa malim brojem informacija o zgradi dostupnih u početnoj fazi i korištenjem tipičnih informacija dođe do informacije o financijskoj isplativosti energetske obnove. Na temelju simulacija sa tim jednostavnim modelom koji je brz i lak za izradu, dolazi se do odluke da li će razmatrana zgrada biti podvrgnuta energetskoj obnovi. U slučaju takve odluke, skupljaju se detaljnije informacije o zgradi te se izrađuje detaljniji i točniji energijski model zgrade na temelju kojega se dolazi do odluke o konkretnim mjerama energetske obnove razmatrane zgrade. U drugom poglavlju još je objašnjena uloga energijske simulacije i BIM-a kroz čitav životni vijek zgrade.

U trećem poglavlju dan je pregled potrebnih informacija za izradu modela za energijsku simulaciju zgrada, kao i pregled pružatelja potrebnih informacija. Slijedeće poglavlje bavi se metodama za prikupljanje podataka o zgradi, najvećim dijelom informacija o geometrijskim svojstvima zgrade, kao i o termodinamičkim svojstvima ovojnice. Opisane su metode od onih uobičajenih, kao što je izrada modela na temelju pribavljene dokumentacije zgrade, preko modernih metoda kao što su lasersko skeniranje, fotogrametrija i termografija do metoda koje su još u fazi istraživanja. Metode u fazi istraživanja navedene u ovom poglavlju omogućuju automatsku izradu 3D modela zgrade, a neke od tih metoda omogućuju i automatsko prikupljanje podataka o termodinamičkim svojstvima ovojnice.

Peto poglavlje donosi pregled najčešćih metoda analize osjetljivosti koje se koriste u energijskim simulacijama zgrada. Analiza osjetljivosti se koristi radi toga da bi se otkrili najutjecajnije ulazne varijable na izlaznu varijablu kod energijskih simulacija. Odabrana metoda za analizu osjetljivosti u ovom radu je, metoda regresije čiji rezultati su prikazani preko SRC (standardized regression coefficients) koeficijenata. Ta metoda je odabrana ponajviše zbog svoje jednostavne i brze primjene.

Najveći trud u ovom radu je uložen u šesto poglavlje, odnosno u praktičan primjer nove metode u planiranju obnove zgrada. Metoda koja je ranije objašnjena, gdje se izradom jednostavnog simulacijskog modela zgrade dolazi do potencijala zgrade za energetskom obnovom, nakon koje se izradom detaljnijeg modela dolazi do odabira rješenja obnove zgrade.

Za primjer napredne metode energijske analize pri obnovi zgrada u ovom radu je odabrana zgrada Alppila srednje škole u Helsinkiju, Finskoj. Školska zgrada sagrađena krajem 1950-ih godina predviđena je za obnovu u svrhu postizanja današnjeg standarda u kvaliteti unutrašnjeg zraka, kao što je mehanička ventilacija sa zadanim protokom svježeg zraka. Uvođenje suvremene ventilacije povećalo bi potrošnju energije, pa je odlučeno napraviti obnovu ovojnice zgrade, da bi se unatoč povećanju kvalitete zraka smanjila potrošnja energije do energijskog razreda B. Prvo je napravljen jednostavniji simulacijski model zgrade, gdje su ulazne varijable prikupljene sa javno dostupnog servisa Google Maps, finskih građevinskih regulativa i iz iskustva. Analiza osjetljivosti je korištena, radi procjene utjecaja koje aproksimirane ulazne varijable imaju na izlazne varijable. Ulazne varijable sa znatnim utjecajem na potrošnju energije su zatim obnovljene naknadnim prikupljanjem podataka, dok su za varijable sa malim utjecajem korištene tipične vrijednosti iz regulative. Nakon što je napravljen jednostavniji simulacijski model, napravljeno je preko stotinu simulacija modela obnovljene zgrade sa mogućim kombinacijama različitih debljina izolacija zidova, krova, poda te tipova prozora. Time su simulirane godišnje energijske potrebe za svako rješenje obnove zgrade. Svako simulirano rješenje je zatim podvrgnuto proračunu životnih troškova zgrade tokom perioda od 25 godina.

Nakon jednostavnijeg modela, napravljen je i detaljniji model. Geometrija tog modela je napravljena na temelju arhitektonskih crteža, dok su podaci vezani uz ovojnicu i termotehnički sustav dobiveni iz strojarske dokumentacije i iz inspekcije same zgrade. Rezultati takvog simulacijskog modela su uspoređeni sa podacima o energijskoj potrošnji dobivenim iz komunalnih računa za zadnjih nekoliko godina. Zatim su napravljene simulacije sa preko stotinu različitih kombinacija debljina izolacije dijelova ovojnice i tipova prozora, te je kao i kod prethodnog modela napravljen proračun životnih troškova zgrade.

Izračunati period povrata investicije kod jednostavnijeg, kao i kod detaljnijeg modela je na razini od otprilike 11 godina. Modeli se doduše razlikuju gledajući njihove pojedine karakteristike. Investicijski troškovi kod jednostavnijeg modela su veći nego kod detaljnijeg, dok su stvari obrnute gledajući godišnji trošak za potrebnu energiju. Rezultati jednostavnijeg modela ne moraju biti isti kao kod detaljnijeg modela, jer jednostavniji model služi samo kao procjena isplativosti obnove promatrane zgrade. Odluke o odabiru rješenja obnove zgrade trebaju se donositi na temelju detaljnijeg modela kod kojega će se provesti i detaljnija analiza isplativosti obnove.

1. INTRODUCTION

The existing built environment is one of the highest consumers of energy (40%) and a significant source of greenhouse gases emissions (36%) in Europe. This fact has been well acknowledged for a number of years, which resulted in an increase in the development of new technologies for energy efficiency, financial incentives by governments to improve the building stock and new legislation to ensure better design and performance. However, despite all these efforts, the replacement rate of the existing building stock remains at 1 - 2% per year only. [1]

There are several reasons for such a small retrofit rate, two of which will be tackled in this Master's thesis. The first is the current inefficient planning, design and construction process with ineffective communication between stakeholders. The second is the missing information about the sources of energy inefficiency in specific buildings and possible energy efficiency measures with their costs and savings.

The problem of inefficient processes and communication has produced many digital innovations in the architecture, engineering and construction (AEC) industry, which resulted in the creation of the cornerstone of future tools and practices in the industry called Building Information Modeling (BIM). The recognition of BIM is reflected in the interest expressed by public authorities in Europe, i.e. the UK government plans to require collaborative 3D BIM on its projects by 2016, with all project and asset information, documentation and data being electronic.[2] Despite these incentives, the BIM paradigm is still rarely applied to retrofit projects due to the difficulties in retrieving the necessary information to build a BIM model, and due to the traditional character of the sector. Furthermore, BIM is mainly used for architectural purposes, while energy aspects are included only at the end of the process as a final validation of the choices already made. A proposal for a BIM-based approach for building retrofit, with a focus on energy analysis, is given in this thesis.

A resolution of the problem of missing information on possible retrofit solutions and their cost information is attempted in this work. This is done by introducing a building energy simulation (BES) at the very beginning of a project. The data available for creating a BES model at this stage is limited, hence, default values from building regulations are used in the analyses, aided with sensitivity analysis to assess the importance of missing information. Sensitivity analysis should provide the importance of an input variable to an energy simulation, depending on the change it caused on the output variable (also known as Key Performance Indicator – KPI). To support this, one chapter of this work is dedicated to the review of sensitivity analysis methods used in building energy simulations.

The missing information which is assessed to be important, should be collected more accurately, and information which is not significant could be left as a default. The idea is that this quick analysis and brief data collection at an early stage helps the building owner and other stakeholders decide if the building will be retrofitted. Furthermore, current and advanced methods (some of them are still in research) for data collection necessary for creating a BIM and BES model are given in a separate chapter.

Another model with a more accurate geometry and necessary information for a BES is created for comparison with a simpler model, as well as for the selection of the optimal retrofit solution. Both created BES models were compared based on the example of the existing school building in Finland, simulating more than 100 possible retrofit solutions. Finally, the most optimal solutions were ranked based on their life cost calculation (LCC).

2. BUILDING INFORMATION MODELING (BIM)

A Building Information Model (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource of information about a facility, which forms a reliable basis for making decisions during the facility’s life-cycle. Life cycle of facility is defined as existing from the earliest conception and design phase, through the construction and maintenance to the demolition phase [3]. A BIM is realized with object-oriented software and consists of parametric objects representing building components. The objects may have geometric or non-geometric attributes with functional, semantic or topologic information. For example, functional attributes can refer to installation duration or costs, semantic information to store connectivity or intersection information (used for clash detection) while topologic attributes provide information about objects locations, adjacency, etc. [4].

The importance of building information modeling for energy analysis is increasing, along with the rising focus on energy efficiency in buildings. At the beginning, a building energy simulation (BES) was done (and sometimes still is) in the late project phase, when the architectural features and the HVAC system type were already defined. Then, a BES model would be created using 2D drawings and manual user inputs for the thermal and HVAC system properties, while the results will not affect the building’s design, as most of it was already defined. Nowadays, BES can be used through BIM as an information source, used from the early conception stage, after which an energy analyst can give feedback to the architect to modify the early building model before moving to the detailed design phase. In the detailed stage, BES can be used for selecting/optimizing building elements for better energy and cost efficiency, and as a decision support for the HVAC designer. After the building is completed, energy simulations with the help of as-built BIM model can be used for energy optimization and for maintenance.

BIM usage breaks the main barrier of using BES, which is work that requires substantial manual input, since an architectural model with defined geometry, orientation and construction elements can now be imported into the BES software. The barriers for a wider utilization of BIM in energy simulations have been the inexistent interoperability between software platforms and the low quality of communication between different participants in the construction process. The first barrier was solved with the open file standard called the Industry Foundation Classes (IFC) developed by international organization buildingSMART. In response to the second barrier, buildingSMART developed the Information Delivery Manual (IDM). The IDM was developed in order to have a methodology to capture and specify processes and information flow during the lifecycle of a facility [5].

BIM functionalities require a certain accuracy, information richness and actuality of underlying data to fulfill their purpose. To standardize information richness, Level of Development (LOD) was developed by the American Institute of Architects (AIA), which is sometimes referred to as 'Level of Detail'. LOD specification is a point of reference that enables practitioners in the Architecture, Engineering and Construction (AEC) industry to specify and articulate the content and reliability of BIM at various stages in the design and construction process with a high degree of clarity. LOD is classified in 6 levels which are outlined in Table 1.

Table 1 A definition of LOD given by AIA [6]

LOD 100	The Model Element may be graphically represented in the Model with a symbol or other generic representation, but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e. cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements.
LOD 200	The Model Element is graphically represented within the Model as **a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation**. Non-graphic information may also be attached to the Model Element.
LOD 300	The Model Element is graphically represented within the Model as **a specific system, object or assembly in terms of quantity, size, shape, location, and orientation**. Non-graphic information may also be attached to the Model Element.
LOD 350	The Model Element is graphically represented within the Model as a specific system, object, or assembly in terms of quantity, size, shape, orientation, and **interfaces with other building systems**. Non-graphic information may also be attached to the Model Element.
LOD 400	The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation **with detailing, fabrication, assembly, and installation information**. Non-graphic information may also be attached to the Model Element.
LOD 500	The Model Element is **a field verified representation** in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements.

2.1. A BIM based approach for building retrofit

An overview of a possible use of BIM technologies in building retrofit projects is given in this subchapter. This approach is not only limited to the retrofit of one building, because it also supports energy analysis and retrofit on a neighborhood (district) level.

In process diagram on Figure 1, BIM-based approach for building retrofit is presented from the energy analyst's point of view. Process diagram shows the whole process of retrofit, from pre-planning (feasibility) phase through construction phase and to building exploitation phase. In the pre-planning phase, usually very little information is available when creating a BES model. Because of that, BES model at this stage matches LOD 200 classification. An energy analyst needs to acquire building geometry information to create geometry model. It is uncommon for existing buildings to have BIM model available, but there is possibility that CityGML model (or similar) exists for that neighborhood or city. If 3D digital geometry model can't be acquired, the analyst needs to create it either by using existing drawings, or by using available mapping services (Google Maps, OpenStreetMap, Here, etc.). Another way of creating 3D model is with advanced data collection methods, such as laser scanning or photogrammetry, which are described in chapter 4. After the creation of a geometry model, the energy analyst assigns other necessary information for BES model (HVAC system, thermal properties, etc.) using available information library. The information library should contain typical envelope elements, HVAC systems, available energy systems, etc. for different building types, ages of construction and locations. Library should be open for updating with new information acquired during the project, so that in future projects model creation would be easier in buildings with similar features. Parameters which are not known in pre-planning phase, should be tested with sensitivity analysis. If sensitivity analysis shows little importance of parameter on output variable, default value from the library could be used. On the other hand, if importance is high, a data collection process should be done for that parameter. When existing building LOD 200 BES model is created, it is stored on BIM/DIM server, where DIM represents a district information model in the case of neighborhood retrofit projects.

After the modeling of an as-is model, the energy analyst simulates possible retrofit solutions (typical retrofit measures should be available in the library) and compares them to the existing model. Other stakeholders (owner, architect, HVAC designer, etc.) should together with energy analyst decide will the building be retrofitted, because energy KPIs which came from energy analysis are not always most important KPIs for making that decision.

In the case when it was decided to continue the work on retrofit of the building, additional data collection phase should begin. This data collection should support LOD 300 BES model creation with accurate building dimensions and other BES input data. This phase could also be assisted with sensitivity analysis. After the as-is LOD 300 BES model was created and verified with energy consumption data, simulation of possible retrofit solutions should be performed again with more accurate data available at this phase. Similar as with a simpler model, the decision on retrofit measures implemented in this project should be done together with other stakeholders.

After the planned retrofit measures get chosen, the design team creates a building model(s) based on information from BIM server. This means that an architect creates architectural model using available BES model, but with additional information needed for his purposes. Similarly, a HVAC designer creates model more suitable for HVAC design purposes by using data already available on BIM server.

After a design model is created, a contractor uses that model to create LOD 400 model with additional information needed for construction phase (assembly information, specific parts data, etc.). Both design LOD 300 model and construction LOD 400 models should be verified by the energy analysis as other stakeholders could make changes affecting building's energy performance (e.g. value engineering).

Once the building retrofit is completed, facility manager creates LOD 500 as-built model using data from LOD 400 model, verifying it with condition on site and adding information needed for maintenance purposes. As-built building model could be used by energy analyst to optimize energy consumption during the building use, or to assist facility manager in maintenance operations.

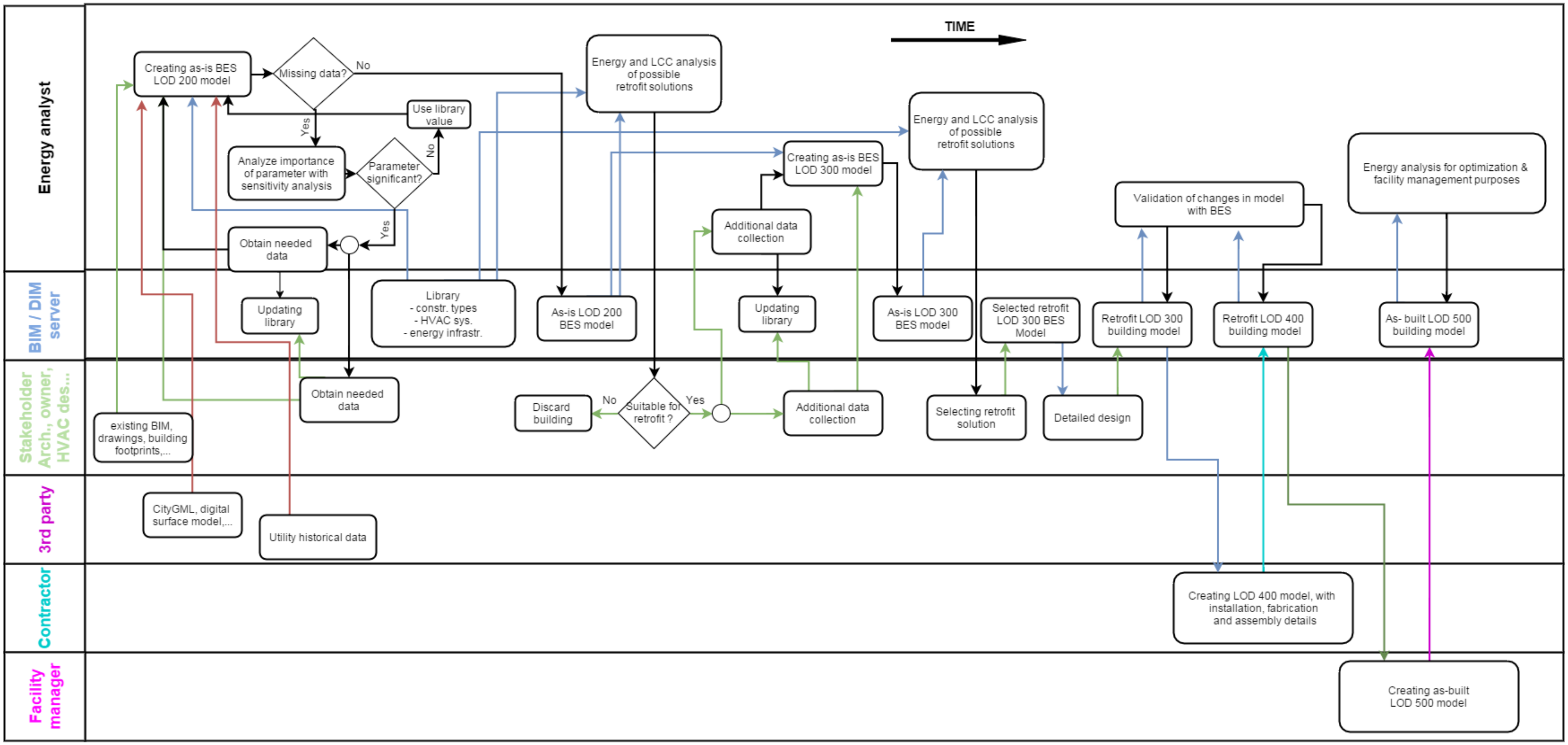


Figure 1 BIM-based approach for building retrofit from energy analyst's point of view

3. DATA AVAILABILITY AND REQUIREMENTS

In contrast to planning new building projects, retrofitting existing buildings poses a far greater challenge in terms of data acquisition, the extensiveness of the acquired data and its accuracy, thus its reliability. Table 2 gives an example of information that are required for building energy simulation. Specific information requirements depend on a simulation software used, a building, HVAC system type and the level of details required for a specific project. The table presents date typically required for retrofit projects of existing buildings in order to make decisions on retrofit measures.

Table 2 Example of information requirements for BES model

Information group	Information required for BES model
Geometry	3D geometrical model with building's shape, orientation and dimensions and it needs to be consisted of: - envelope elements (walls, floors, glazing) - spaces / zones - building adjacency (example: sharing wall with other building) - shading elements
Building envelope	Thermal properties of building envelope elements such as: - heat transfer coefficient (U-value) - transmittance of glazing elements - thermal mass properties
	Reflectance properties of materials
	Infiltration rate
	Thermal bridging
HVAC system	Type of HVAC system
	Energy sources

	Properties of HVAC system type such as: - system efficiencies (generation, distribution) - type of heat recovery system - specific fan power (or system pressure drop and fan efficiency) - etc.
	Operation schedules
	Domestic hot water system properties - consumption - DHW generation system properties (type, efficiency, etc.)
Indoor comfort	Set-points (cooling/heating temperature, humidity, CO_2 level, etc.)
	Airflows
Interior thermal loads	Thermal loads produced by : - people (depends on activity performed in space) - lighting - equipment (computers, machines, etc)
	Occupancy patterns and load profile
Utilities	Historical energy and water consumption
Weather	Location of building

Data collection for the energy analysis through simulation of existing buildings can be problematic. Most of the required data are often confined within the built structure, and available records do not accurately reflect the up-to-date state of the building due to the numerous changes that occur along the buildings years of operation. In the Table 3 example of possible data providers is given along with data they can provide. Required data that cannot be obtained from these data providers needs to be collected on the building site; more information on those methods are given in following chapter.

Table 3 Example of possible data providers and provided data by them

Data providers	Provided data
Architect	Drawing & specifications, materials used
Civil and mechanical engineer	Drawings, specification & calculations, materials used, building systems used
Utility company	Energy and water consumption
Contractor	Drawings, specifications, bill of quantities
Owner	Building documentation, building use, location, HVAC system types, operational schedule
Building management	Energy consumption, operational schedule of building, HVAC types, interior loads
Occupants/ residents	Heating/cooling set points, operational schedule, number of occupants, presence during hours of use, activity, clothing, lighting types
Manufacturer/retailer of systems, elements and materials used in building	Technical specifications

4. DATA COLLECTION METHODS

A 3D model is needed to create a Building Energy Simulation (BES) in a BIM-based approach. Existing buildings very rarely possess a 3D model, so an energy modeler needs to undertake a time consuming and complicated process. A 3D simulation model does not only need to have a 3D spatial CAD model, but also consist of building elements with their belonging properties, as well as contain information about interior loads, climate and HVAC system. For this reason, it can be beneficial to use the BIM approach, where each stakeholder provides information related to their expertise, and an energy analyst then uses that information to create an energy simulation model. This chapter will describe the most common data collection methods currently used to carry out the BIM based approach in an existing building retrofit, as well as interesting advanced methods.

4.1. Current data collection methods

Most of the data for energy analysis is currently collected during a manual energy audit, where a qualified engineer visits the building, interviews the facility manager and documents the necessary data. The engineer walks through the building one room at a time, noting down the construction details, room temperature, light and equipment levels, HVAC components, the condition of the building and its parts, etc.

The 3D geometry is usually created based on the floor plans, while the thermal properties of the envelope are obtained from the drawings and the site visit. More information on current geometry and thermal properties data collection methods is given in the following sections.

Interior loads, air quality, schedules and HVAC system information is still acquired purely manually. There are two possible approaches:

- Detailed data collection – example: counting light sources and their types, counting and measuring the plug load equipment, checking air quality parameters (temperature, humidity, airflow, etc.), specifying HVAC and control components, extracting data from the BMS (Building Management System), etc.
- Data collection through approximation – example: using typical values for a given room type (lighting, equipment and people load per floor area, typical schedules), obtaining only the HVAC system type and then using the template model for the same type, etc.

It often occurs that data collection is a combination of both approaches, where the analyst determines which data is assumed and which is measured.

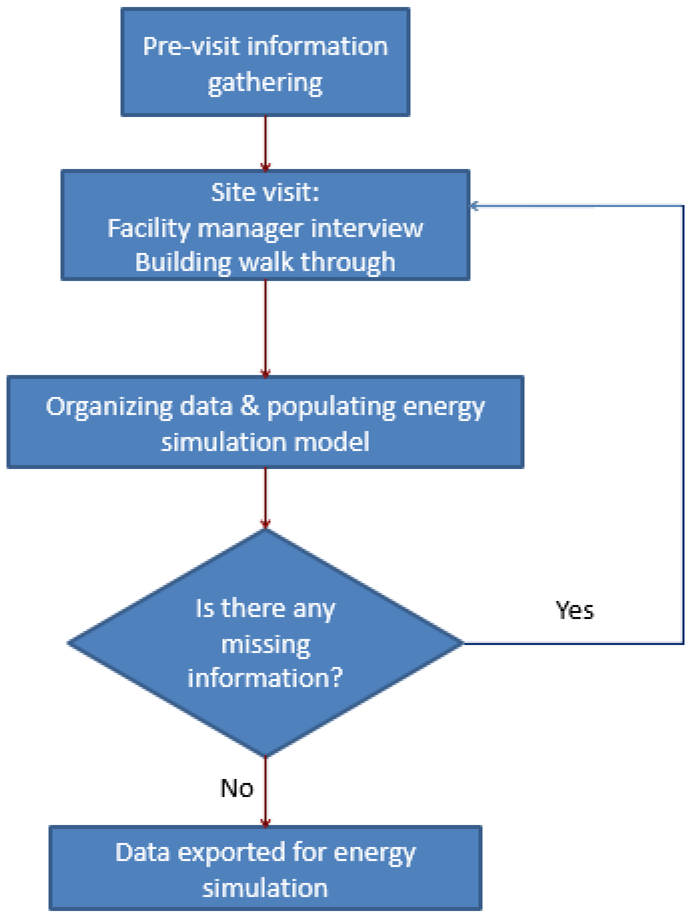


Figure 2 Flow chart describing the manual data collection process

Figure 2 shows the typical procedure for data collection during the energy audit. Data is collected in three parts: before the visit, from the facility manager, and during the building walkthrough. Afterwards, the analyst studies the collected data, which is often unorganized (digital and IR photos, drawings in different formats, spreadsheets, notes, etc.) to prepare the information necessary for input into the energy simulation. During that process, the analyst sometimes discovers that certain data is missing, which requires the analyst to go back to the building site. Consequently, the efficiency of the current data collection process is not as high as it should be.

4.1.1. Geometry data collection

Manual modeling is the most commonly used process for creating the building geometry model as an input to the BES. Data sources for manual modeling are usually existing 2D drawings and floor plans, as well as measuring, sketching and photographing the building while visiting the site. If there are complete technical data on the existing building, they are often outdated, because of smaller and larger changes that have been executed over the years to the building envelope and in the floor plans, often undocumented or unorganized. Hence, checking on the site is most often required prior to modeling. Manual methods are problematic if the goal is to increase the rate of buildings under retrofits, and especially if the goal is to increase the use of BES and BIM in retrofit projects. Furthermore, measuring, sketching and modeling are error-prone and time-consuming processes, particularly if a high LOD (Level of Detail) is required.

4.1.2. Thermal properties data collection

For the simulation of energy performance of an existing building it is very important to know the thermal properties of building elements in addition to building's geometry. Usually, the materials used in construction can be found in the building documentation, which enables one to find material properties. Even in cases with a sparse documentation, an experienced modeler can assume and examine which materials have been used depending on the year of construction, type of wall, local climate, etc. However, this approach can lead to certain problems:

- the energy modeler has incorrectly assumed the materials used
- changes have been made to the building envelope over the years, which have not been documented
- materials that have been used during the construction phase are different from those documented, and/or work that was done was of poorer quality
- materials degraded over time, which lowered their thermal properties

For a more accurate assessment of heat flow (U-value) through the building elements it is possible to use IR thermography, or even a surface thermometer. If one knows the inside wall temperature and the difference between the outside and the inside air temperature (the difference needs to be sufficiently high), and if the steady-state heat transfer is assumed, it is possible to calculate U-value with precision of around 10-12 % [7]. It is also important to note that thermal imaging is very sensitive to the surrounding conditions (reflections, shadows, wind, sun radiation, etc.), which needs to be taken into consideration during the measurements. With an IR camera, it is possible to analyze thermal inconsistencies in the wall and spot thermal bridges. However, because of the small resolution of IR cameras it is necessary to acquire a large number of images and their processing and handling can be problematic.

4.2. Advanced data collection methods

Acquiring data of an existing building in a digital format can be done with the use of modern technology. Technology development for data collection has gone the furthest in the field of geometry scanning methods, while the process for thermal data collection is developing in the direction of automatic IR image processing and storing. Although some of the methods that are described in the following sections have existed for some time, they are still rarely used for the energy retrofit of buildings and even less often for creating building energy models.

Regarding data collection of HVAC and the control system equipment, the most advanced method is still a manual energy audit done by a qualified engineer. With the use of web technologies and mobile applications it is possible to simplify data collection for the engineer on the building site and reduce the necessity of returning to the site if afterwards during the analysis it is discovered that certain information is missing. With the help of the mobile application, the engineer could access the information about the building that are already available, access the library with typical building systems, attach photographs and input additional information while on site.

4.2.1. Advanced 3D geometry data collection methods

4.2.1.1. Laser scanning

Laser scanning with LIDAR (light radar or light detection and ranging) or with a ToF camera (Time of Flight camera) is a remote sensing technology that measures distance by illuminating a target with a laser (in case of ToF, other light sources are possible) and analyzing the reflected light. In order for an object to be described, the laser needs to target as many points of the object as possible (according to the scanner´s resolution), which is done by either reflecting the laser beam from a rotating mirror or by mounting the laser on a rotating stand. The result is given as a point cloud model, which is a set of 3D points in a coordinate system representing the surfaces of a scanned object. The point cloud model cannot be directly used as a 3D model, because it requires a process known as surface reconstruction, as discussed in 4.2.2. [8]**.**

Figure 3 3D laser scanner [9]

4.2.1.2. Photogrammetry

Photogrammetry is a technique of making measurements using photographs, and the version of photogrammetry that is interesting in the context of creating 3D models is called stereophotogrammetry. Stereophotogrammetry estimates three-dimensional coordinates of points using two or more photographs of the same object, taken from different positions. A set of 3D points in a certain coordinate system (example: points in x, y, z direction) provides a point cloud model. Photogrammetry is a simpler and more affordable method than laser scanning, but less accurate. Nowadays, there are 3D scanners that are equipped with a laser scanner and a digital photo camera, which enables the creation of a colored point cloud model [10].

4.2.2. From a point cloud to a BIM model

Currently, there is not a fully automatic way to obtain a BIM model out of a point cloud, because there are many issues with the point cloud caused by the 3D scanning process. For example, if certain parts of a building were in a shadow from the point where the scanner was positioned, those parts will be missing in the point cloud, hence, a piece of software would need to have an intelligence capable of redrawing the missing parts. Furthermore, existing buildings are often occluded with furniture, equipment, plants, and other objects that would be caught on point cloud. Finally, buildings, especially very old ones, have many details which are not relevant for the BIM, especially not or the BES, and including these details would make the modeling and the simulation unnecessarily more complicated.

Current BIM software that have the ability for the input of large point clouds is functioning in a manual way, or at best in a semi-automatic way to create elements from the point cloud data. The manual way (example: Autodesk Revit) is using a cloud point as a reference model, meaning that the modeler needs to remodel the building and its elements with a point snapping technique. The semi-automatic way (example: Revit add-ons such as PointSense or Imaginit's Scan to BIM) allows the user to select the elements in point cloud, and then the software uses 3D coordinates to create surfaces of selected points. The user can define those surfaces as part of an element, populate them with extra information and finally export as a BIM model [4], [11]–[13].

4.2.2.1. Interior model creation

The process of scanning of every room on every floor from inside of the building can be time-consuming and often unnecessary. It is especially problematic when the interior spaces are occluded with elements (furniture, equipment, people, etc.). However, there are software solutions which can combine a 3D building envelop model with 2D floor plans. This enables fast creation of interior 3D models, as well as an easy integration with the BIM [4].

4.2.3. Advanced data collection methods currently in research

Recently, substantial research was done on hybrid methods, which can perform geometric data collection, while some of them can even simultaneously perform thermal data collection and create a practical visualization of the collected data. The following section gives examples of the advanced data collection methods that can be found in research journals.

4.2.3.1. Image fusing and matching method

The RAAMAC (*Real-time and Automated Monitoring and Control Lab*) team from the University of Illinois is developing a method which would enable a rapid generation of 3D thermal models by collecting multiple thermal and digital images (Figure 4) A single thermal camera is used for simultaneously capturing digital and thermal images, after which the images are post-processed using computer vision algorithms, such as Structure from Motion and Multi-View Stereo to automatically generate a dense 3D point cloud of the existing building. Similarly to the method explained earlier, in which a 3D thermal point cloud is created from thermal images and then integrated with a space 3D model, in this method the 3D environment is created as a spatial-thermal model. The spatial-thermal model is visualized in a way that enables a virtual walk-through of the building, which in turn provides a practical way to catalog large number of thermal images from different parts of the building. However, digital imaging and thermography have quite different requirements for the production of a good image; digital imaging requires a well-lit surrounding, while thermography is better done at night, meaning that it is not always possible to collect both types of data simultaneously [14].

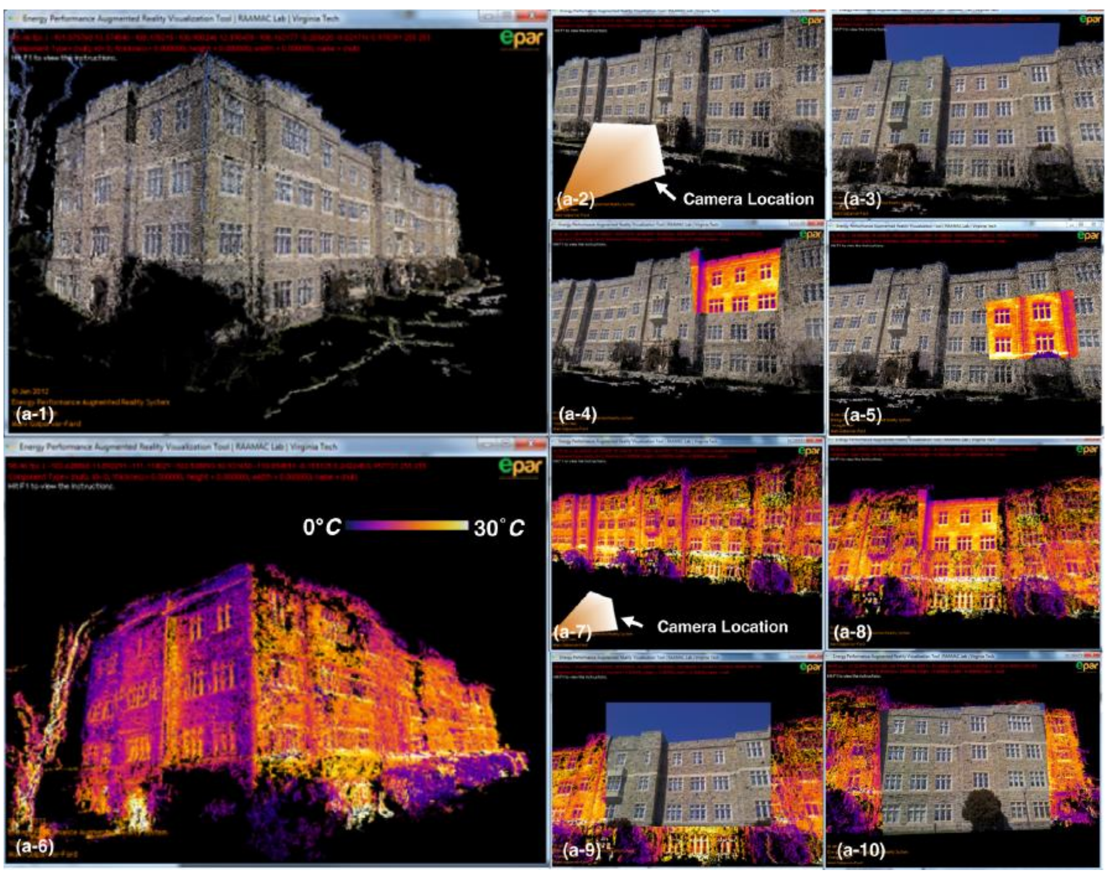


Figure 4 3D building and thermal point cloud models and visualization software [14]

4.2.3.2. The hybrid LIDAR system

Wang C. and Cho Y.K. [15] have developed the 3D LIDAR system with an integrated IR camera used for geometrical and thermal data model collection (Figure 5). The LIDAR scanner is used for creating point clouds of desired objects, while the IR camera is simultaneously collecting temperature data from the same object. The temperature data is automatically fused with the corresponding points during the data collection process, after which the noise filtering is applied. Additionally, the same team has developed a window detection algorithm, which detects transparent windows and blinded windows and includes them in the 3D model. Since the beam from the LIDAR scanner passes through transparent surfaces, surfaces such as windows could not be modeled without an algorithm. Finally, the 3D thermal model is visualized in a graphical user interface (GUI) and includes the temperature data for every point. In comparison to the image fusing and matching method, this method does not require a well-lit environment, which means it is easier to take high quality thermal images. However, it is a more expensive method and a more complicated one, as it requires a specially trained person to operate the LIDAR scanner. [15]

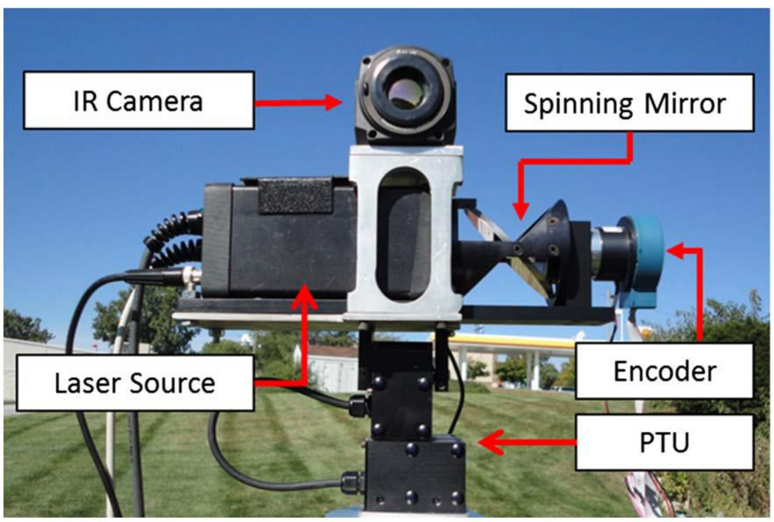


Figure 5 The prototype hybrid thermal LIDAR system [15]

4.2.3.3. Rapid Building Energy Modeler (RAPMOD)

The compact 3D data collection method that is being developed by a collaborative research team from Berkeley Lab, the University of California, Berkeley and Baumann Consulting is called Rapid Building Energy Modeler (RAPMOD). RAPMOD (Figure 6) consists of several sensors capable of creating 3D point clouds (such as LIDAR), a photo camera, an IR camera, a thermometer and a sensor for identifying window glass types. The IR camera is used to collect data regarding thermal properties of the building envelope, and to identify indoor heat sources such as lighting systems, occupants and equipment. RAPMOD also uses a window identification algorithm, which locates windows on the exterior walls and estimates their size. It even takes into consideration blinds and obstructions. Mounted on the device, there is also a glass checking sensor (Glass-Check PRO GC 3000), a handheld device which, when touched to the window, calculates the U-value from its record of layers and films it can identify. With all this equipment compactly packed as a backpack, and with the software that controls all the functions of the RAPMOD, there is no need for a qualified engineer to do the data collection; instead, a trained technician can do the work.

RAPMOD has been tested on an academic building at the Berkeley's campus, and the results were compared with a manually performed energy audit [16]. In that study, RAPMOD's geometry data collection was compared to the model manually created from the floor plans. The geometry captured with RAPMOD was 12% less in floor area than the manually created geometry. However, the problem was not technical, but of a more practical nature, with the operator being unable to enter all the spaces in the building. The other problem with the geometry was that certain thermal zones (rooms) were created differently than in the manual model, as the computer algorithm recognized certain barriers in the room, such as walls which divide the space. The automatic calculation of the window-to-wall ratio resulted in about 11% less ratio than with the manual method, as RAPMOD was scanning the building from the inside, hence, was not able to account for the wall area between the ceiling of one floor and the ceiling of the floor above.

Using visual recognition algorithms and infrared imagery, RAPMOD was able to identify the lighting loads in each space. When compared to the manual counting of light sources and specifying their consumption, the overall lighting level only differed by 0,6 W/m^2 for the entire building. With similar technology, RAPMOD was able to identify and calculate the power consumption of computers in the space with great accuracy, with the only problem being that it could not yet identify other equipment.

In conclusion, RAPMOD collected and processed large quantities of data, which were then implemented by an analyst into an energy model. The overall energy consumption results were within 6% of the manually created model and three percent of the three year averaged utility data. Looking at the time required to collect the data, RAPMOD was 84% faster than a manual model when taking into account only the variables which RAPMOD can collect, and 55% faster overall [16].

Figure 6 Rapid Building Energy Modeler (RAPMOD) (source:[17]**)**

4.2.3.4. Project Tango

Project Tango is a Google technology platform that uses computer vision to enable mobile devices, such as smartphones and tablets, to detect their position relative to the world around them without using GPS or other external signals. This allows application developers to create user experiences that include indoor navigation, 3D mapping, measurement of physical spaces, recognition of known environments, augmented reality and windows into virtual 3D worlds [18].

The Yellowstone tablet is a tablet with full Project Tango functionality and it features a color camera, a fisheye-lens camera and an integrated depth sensor. In its current phase, the tablet is available to application developers, who can create Android applications that use the featured sensors.

Figure 7 A Google Project Tango Yellowstone tablet [19]

A research group from ETH Zürich led by Marc Pollefeys has developed a system for quick 3D reconstruction of large-scale outdoor scenes by using a Project Tango tablet. All calculations from the sensor data are performed in real-time on the tablet's GPU and the collected 3D data is shown on the screen [20]. This enables the 3D geometry data collection of a building, or even a district in a short time.

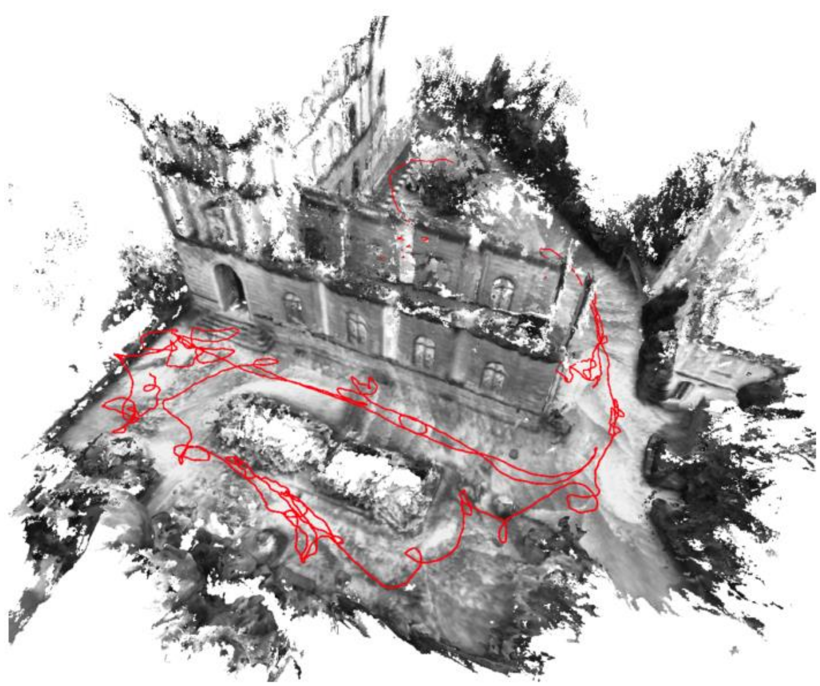


Figure 8 A model reconstructed by ETH research group's system running at interactive frame rates on a Google Project Tango Tablet, with the camera trajectory shown in red [20]

5. SENSITIVITY ANALYSIS

Sensitivity analysis is an important tool in building energy analysis, where it can be used to find the most influential input variables. It is often mistaken for uncertainty analysis, which is why it is important to emphasize the difference. Uncertainty analysis refers to the probability distribution of the dependent variables (outputs), while sensitivity analysis refers to the rank of the most important variables (inputs) that generate the variation in the output [21].

The structured process for performing a sensitivity analysis is always the same, regarding which method of sensitivity analysis is being used.

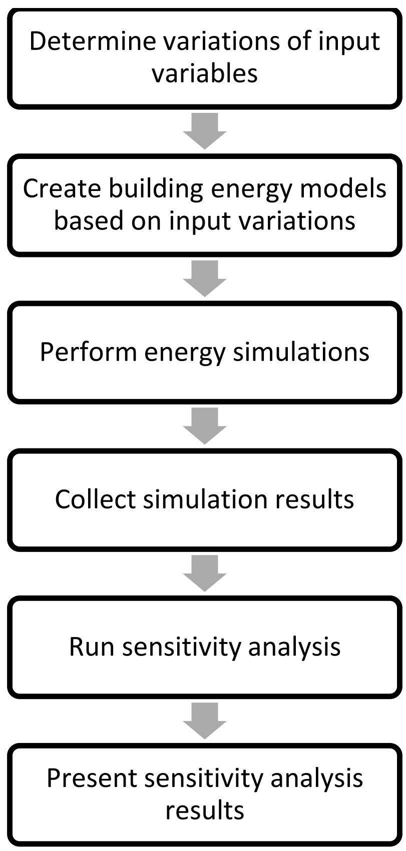


Figure 9 Typical schematic diagram for sensitivity analysis in a building performance analysis

In Figure 9, a typical schematic diagram describing the structured process for a sensitivity analysis can be seen. The first step is to determine the variations of the input factor and their probability distributions (more information on that will be given later in the text). The width of the selected range of input variables is very important; hence it affects the sensitivity analysis. For example, if a variable A has a small influence on the output values, and variable B has a high influence, but the range of variations of variable A is wide and of variable B is narrow, the resulting sensitivity analysis can give the impression that variable A is more influential. Therefore, it is important to choose a range wide enough to analyze all possible options, but no wider than that. The second step is related to creating building energy models based on defined input variations. In sensitivity analysis there are usually many possible combinations of input variables, which would require time-consuming computations. Hence, it is inconvenient to calculate every possible case, and is recommended to create a random sample from the possible combinations, taking into consideration input probability distributions. In this work, a simple random sampling will be used since it was shown that there is no significant difference in results between different sampling techniques used for sensitivity analysis [22]. After the energy simulations are completed, the following two steps are the processing and the analysis of simulation results. Several methods that are commonly used for sensitivity analysis in building energy simulations are discussed in more details in the next section. The last step is to visualize the results obtained from the sensitivity analysis. The presentation of the results can depend on the method used for sensitivity analysis, the purpose of using sensitivity analysis and other reasons.

If using sampling-based methods, it is very important to consider probability distributions of input variables. In the case where one is comparing different design solutions, input variables should be taken as uniformly distributed, since the designer wants to explore all possible design solutions with the same relevance. In the case of a performance analysis of an existing building, in most cases it is better to use normal distribution since those variables are most likely to be constant, with small variations due to a lack of knowledge, natural degradation, etc. [23].

5.1. Most common sensitivity analysis methods in a building performance analysis

5.1.1. Local sensitivity analysis

Local sensitivity analysis, also known as differential sensitivity analysis, is the simplest sensitivity method to understand and to implement. It belongs to the class of one-factor-at-the-time methods. The sensitivity analysis is performed by changing one factor while the others are fixed, which makes the selection of the base case for the analysis very important. To quantitatively assess the sensitivity, the influence coefficient (IC) is used, which is defined as:

$$IC = \frac{OP-OP_{BC}}{OP_{BC}} / \frac{IP-IP_{BC}}{IP_{BC}} \qquad [1]$$

where *OP* is output variable, *IP* input variable and *BC* base case.

There are several drawbacks to the local sensitivity analysis method [24]:

- it only explores the reduced space of the input factor around a base case
- this method does not consider the interactions between input variables
- the method does not allow any self-verification; i.e., the error of the analysis cannot be estimated directly from its results

5.1.2. Global sensitivity analysis

Global sensitivity analysis is a group of sensitivity analysis methods that take into account variations of multiple variables at the same time, depending on the shape of their probability distributions and ranges. This section, describes the most often used global sensitivity analysis methods in building energy analysis [21].

5.1.2.1. Regression method

The regression method is the most widely used method for sensitivity analysis in a building energy analysis, because this method is fast to compute and relatively easy to understand. With this method it is possible to change each input variable and analyze its influence on the output, without a base case. Since there are often too many combinations of input variables, it is necessary to perform Monte Carlo analysis. This means creating a randomized sample with a reasonable amount of combinations, which are then simulated and analyzed. A regression method analysis takes output and input values and finds coefficients that describe output value from given input values. The following is the form of a regression equation:

$$y(x_1, x_2, x_3, \dots, x_n) = \beta_0 + \sum_{j=1}^{n} \beta_j x_j \qquad [2]$$

where y is the predicted output value (e.g. heating, cooling, total energy), x_j represents the input value of design variable j, and β_j is the corresponding regression coefficient. The next step is to normalize the regression coefficients, because of the difference in the magnitude of regression coefficients β_j, which depend on the units of x_j (example: building area of 2800 m^2 and window U-value of 1 W/m^2K). Linear regression coefficients can be normalized into standardized regression coefficients (SRCs) to allow for comparison. To obtain the SRCs, every coefficient needs to be multiplied by the ratio of the estimated standard deviations (s) of x_j to y:

$$SRC(x_i, y) = \frac{\beta_j \times s_{xj}}{s_y} \quad [3]$$

Once the regression coefficients have been normalized, the sensitivity of variables can be quantitatively compared by using the calculated the SRC values. Hygh et. al. came to the conclusion that in some cases SRC normalization suppresses the estimated absolute variable sensitivity, which means it is better not to use normalized coefficients when comparing the variables of the same unit [25].

When the relationship between the input variables is non-linear, a regression analysis can perform poorly; in that case it is recommended to use Standardized Rank Regression Coefficients (SRRC) instead of the SRC. The procedure called rank transformation is a simple procedure where the data is replaced with their corresponding ranks (the smallest value is assigned rank 1 and the ranking continues to the largest value which is assigned rank N). Then, the usual regression process is performed based entirely on assigned ranks, which provides an extremely satisfactory performance when the model output varies linearly. However, rank transformation alters the model under study, so the resulting sensitivity measures a different model (with rankings instead of values) from the original one, which makes the SRRC analysis a somewhat qualitative measure [26].

For correlated inputs it is possible to use a PCC (Partial Correlation Coefficient) [27], which provides a measure of variable importance that tends to exclude the effects that other input variables have on the observed one. If there is no correlation between the input variables, the PCC will show the same ranking as the SRC. Compared to a SRC analysis, an analysis based on the PCC can give very misleading results in case of high correlations between inputs. Specifically, in a case with two highly correlated variables, the PCC will cancel out their mutual effect, and the analysis will give an impression like neither of them have an effect on the output [26], [27]. The description of most preferable methods (rather than regression methods) to be used in the case of correlated inputs can be found in [23].

5.1.2.2. Morris method

The Morris method is the screening based method, which is used for ranking input variables by their influence on the output. The so-called one-step-at-a-time method gives a new value to only one parameter in each run. This continues until all input variables are changed, after which the entire procedure is repeated *r* times (where *r* is usually between 5 and 15), each time with a different set of start values. The final sensitivity measures are calculated by averaging at different points of the input space.

This is a computationally efficient method able to capture interaction effects among variables. It is suitable when there are a few influential factors and a majority of non-influential factors. The downsides are that it does not allow self-verification, as it is only a qualitative measure which cannot quantify the effects of different factors on outputs, and it does allow for an uncertainty analysis [23], [28].

5.1.2.3. Variance-based method

In the variance-based method two different sensitivity measures are used: first order effects and total effects. The first order effects consider the main effects for the output variations due to the corresponding input. The total effects account for the total contributions to the output variance due to the corresponding input, which include both first order and higher-order effects because of interactions among inputs. In other words, while first order effects are useful when checking the main energy consumption drivers, using total effects analysis would help with removing influence of unimportant variables. Finally, using both measures would help with finding interactions between variables. There are two commonly used variance-based methods, Sobol and FAST (Fourier Amplitude Sensitivity Test). It is important to note that FAST can only consider nonlinear effects, not the interaction effects. Sobol is particularly computationally expensive, but both of them have been used for the exploration of building energy performance [23].

This method is regarded as a model free method, which means it is even possible to use nonlinear complex models and non-additive models in analysis. The disadvantage of this method is that it comes at a high computational cost.

5.2. Selecting the most appropriate method

When selecting the right method for sensitivity analysis for building energy performance analysis, it is important to consider the following:

- The method needs to quantify the importance of input variables, and not be used only to provide their rank. The importance of input variables does not need to be specific, it can be relative.
- The sensitivity of variables should be calculated in a shorter time than the time necessary for running a large number of simulations that are needed as an input.
- The method should allow the use of discreet variables.

The preceding statements have rejected variance based methods like FAST and SOBOL, as they require high computational time and their application is challenging. Furthermore, the FAST method is not applicable for a use with discrete variables. The Morris method is also disqualified because it belongs to qualitative methods, which means it shows only the rank of variables, but not their importance. The remaining methods are the local IC method and the regression method, which are the most commonly used sensitivity analysis methods due to their simplicity and shorter calculation times.

The local sensitivity analysis method, despite its simplicity, will not be selected, due to its drawbacks, such as:

- The results vary depending on the selected base case, therefore, selecting a different base case would produce different results.
- The local method does not consider interactions between variables, which means that when several input variables are changed at the same time, their influence on output is not the same as the sum of their individual influences.

The regression method, which provides the relative importance of variables, is easy to calculate, easy to understand and takes into consideration the interactions between variables. The next step is to choose the right indicator for the regression method. Rank transformations of the regression method (SRRC and PRCC), as discussed earlier, are performed on assigned ranks and not on real values which gives qualitative results, therefore, they are not going to be included in this work. The SRC and the PCC give the same ordering for uncorrelated inputs, but the PCC results are more spread out and sometimes it can appear that the variable has a larger effect than it actually has [27]. The correlation of inputs in a building energy simulation is not considered in the majority of the research in this area so it will not be included here. In conclusion, the SRC is the most suitable result indicator of the regression method in building energy analysis [23], [27], [29].

5.3. The use of sensitivity analysis in building energy simulations

Sensitivity analysis in building energy simulations is used to find the most influential input parameters for the simulation. So far, sensitivity analysis has been used predominantly in the design phase of buildings, to help designers and decision makers locate influential inputs and adjust the design accordingly. Sensitivity analysis could also be used in the preliminary stage of retrofit projects, as support for additional data collection.

5.3.1. Sensitivity analysis as a support for data collection

In this work, it is suggested to utilize the BES (Building Energy Simulation) from the beginning of a project. In the first phase of the project, very little information is available to the energy analyst; additionally, this information usually has a low level of accuracy. As a result, unknown variables that are the inputs to the BES are approximated using default values (usually provided in country specific regulations and standards) and/or with the help of the analyst's previous experience. Even though the true value of the variable is unknown, the effect of the variable on the Key Performance Indicator (KPI) (energy consumption, CO_2 emission, etc.) can be evaluated with the use of sensitivity analysis. For each specific KPI, there should be a separate sensitivity analysis, ranking variables by their influence on that KPI. The effect of input variables on the KPI value can be then used for ranking the importance of acquiring more precise information.

To make the process of a sensitivity analysis in a data collection phase more understandable, an example is given below.

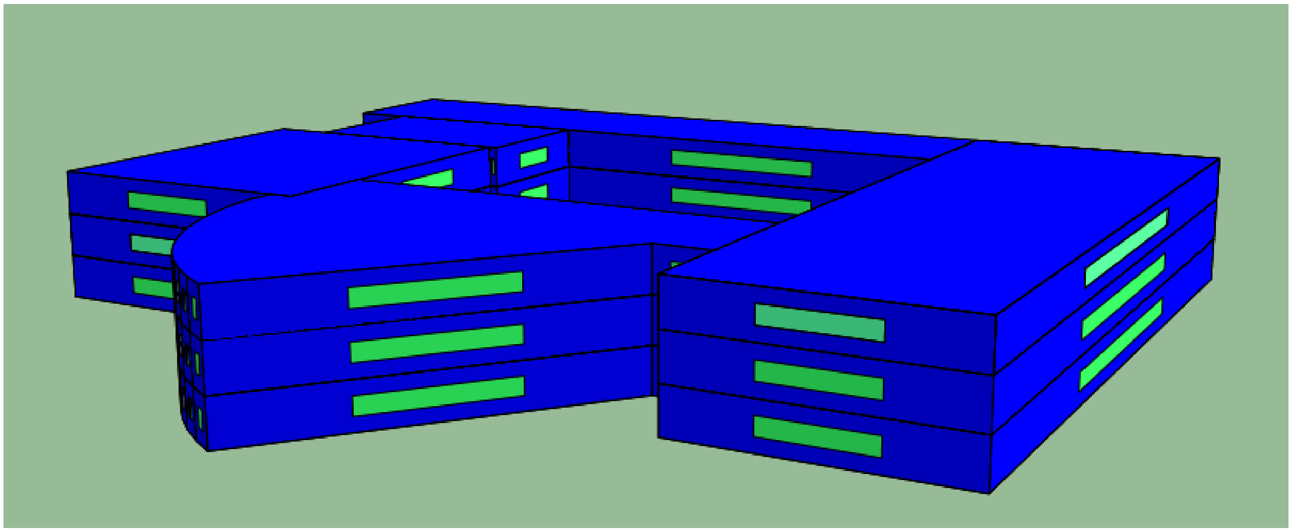


Figure 10 Example case with an LOD 200 model building and approximated window/space area

An analyst is given the task to analyze energy consumption of a particular school building based on the existing LOD 200 model (Figure 10). The model contains the approximate size, shape and orientation of the building, along with its location. Many of the necessary input variables for BES are unknown (such as the thermal properties of the envelope, the ratio of the window area per external wall area, etc.) and the analyst needs to assume their values. The estimation is performed by using the default values which come from country specific regulations, the construction library or from the analyst's personal experience. Since these values are just estimation, it would be valuable to explore the possible range of the values by using sensitivity analysis. Since the selected range has a significant impact on the sensitivity results, the analyst should, focus on the selection of possible variations based on the assumed values.

After the selection of possible input values and random sampling, energy simulations are performed, followed by a sensitivity analysis. The results obtained from the sensitivity analysis can suggest which input variables need to be identified more precisely, and which ones could be specified as a default value. In Figure 11, the results obtained from the sensitivity analysis for the primary energy need KPI are shown as ranked columns with their SRC values. It is important to keep in mind that the SRC values do not provide any concrete meaning, merely a relative sensitivity coefficient of the variables compared to each other. In this example, the sensitivity analysis ranks light load, airflow and infiltration value as very important. It suggests a high importance of acquiring these data before continuing with the retrofit planning project. Although wall and floor U-value, equipment load and heating system distribution efficiency have a lower significance on energy need, they are still significant, and should, therefore, be approximated with higher accuracy. On the other hand, the fact that several variables in this example, such as roof U-value and specific fan power (SFP) show a small effect on the KPIs means that an analyst can use default values in this case, without much effect on the final result. The default value could also be used with variables which are not planned to be retrofitted, or with variables that could be very difficult to obtain.

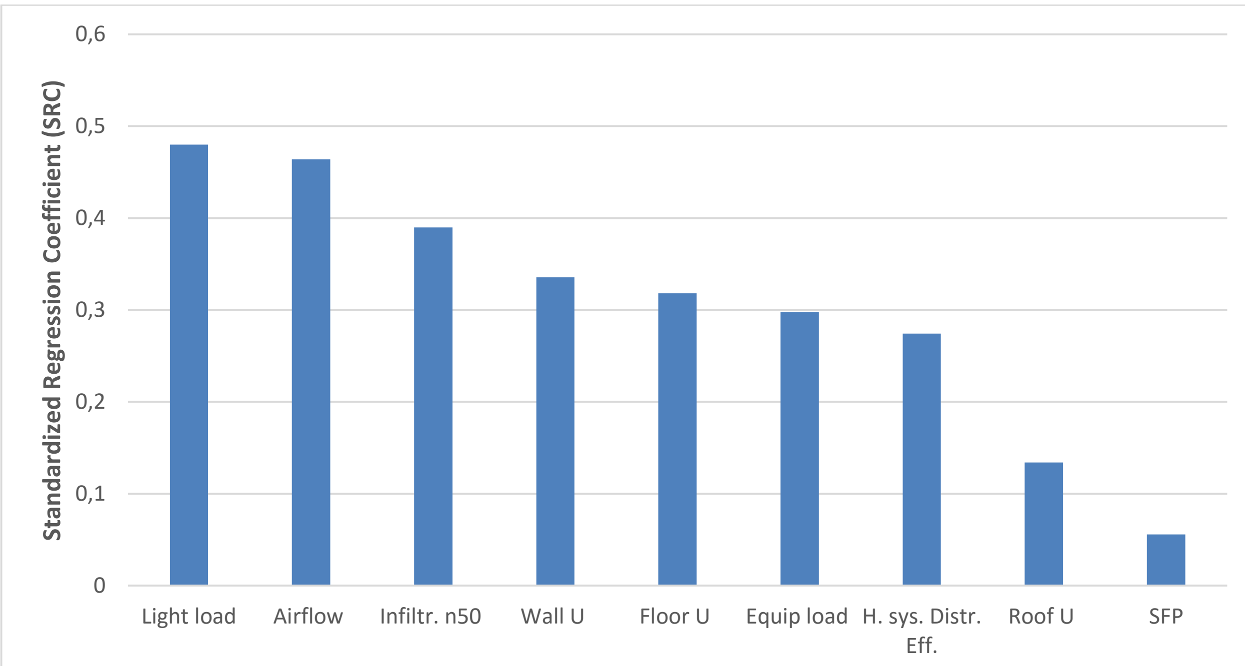


Figure 11 Example visualization of the sensitivity analysis results for the KPI of the primary energy need in the preliminary phase

5.3.2. Sensitivity analysis as a support in the design and planning phase

The next phase of the retrofit project starts when all the necessary data are obtained, and the simulated building consumption is verified using real consumption data from utility bills. The selection of the optimal retrofit solution should be supported by using sensitivity analysis that indicates which variables have the strongest impact on the energy consumption. Compared to the sensitivity analysis from the preliminary/data collection phase, the considered range of input values in this analysis should correspond to the possible retrofit options.

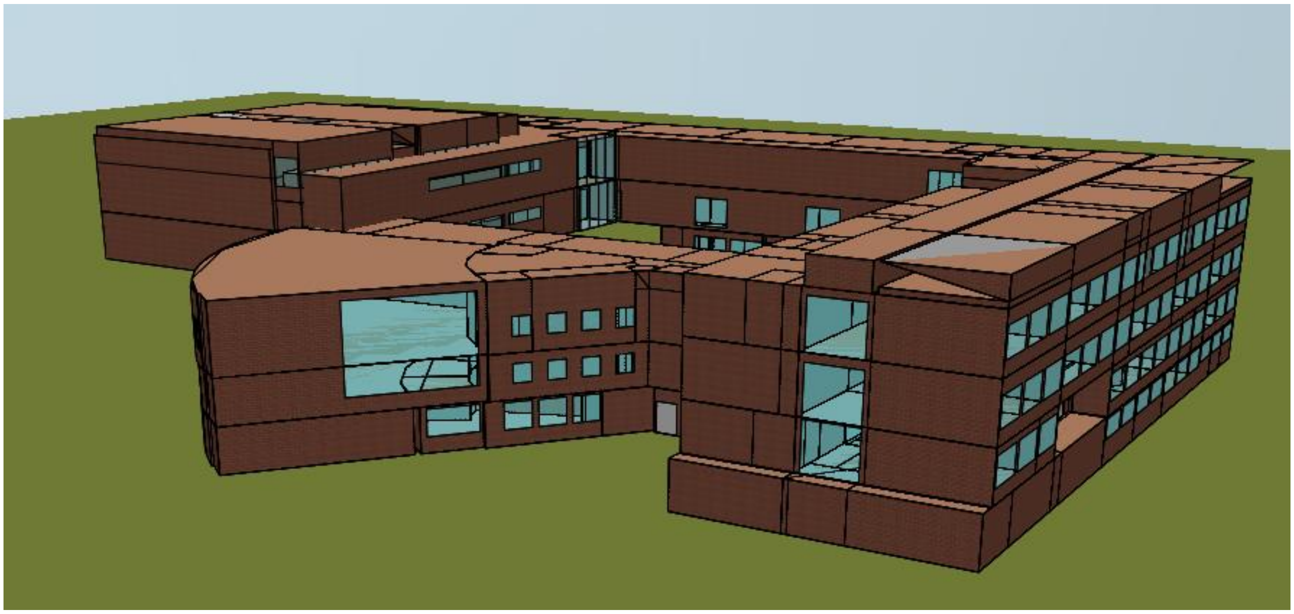


Figure 12 Example case with an LOD 300 building model

The collected information for this phase should represent an LOD 300 building model (Figure 12) with more accurate data on the building fabric, interior loads, climate, schedules and HVAC systems. The energy analyst, together with the other stakeholders, should asses all possible retrofit changes in the building, after which a random sample of those possibilities (or all possibilities if their number is not too high) needs to be simulated and included in the sensitivity analysis. It is often recommended to perform building energy simulations in several iteration steps, as redefining the chosen variables and their ranges will affect the variable sensitivities considerably [30].

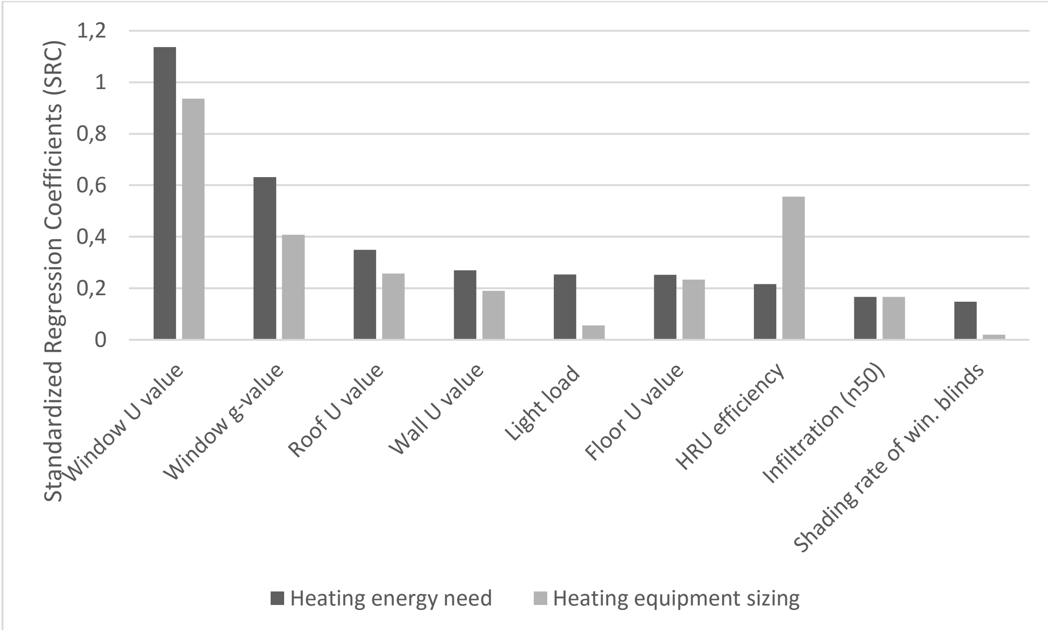


Figure 13 Example visualization of the sensitivity analysis results for heating en. need and heating equipment sizing KPIs in the design phase

In Figure 13 the visualization of the sensitivity analysis results can be seen for heating energy need and heating equipment sizing KPI parameters. In this example, it can be observed that for the given retrofit options, the window type has the highest impact on both of the considered KPIs and that the Heat Recovery Unit (HRU) efficiency has a high impact on the heating equipment sizing, but not as high on energy consumption. HRU affects more sizing, because sizing is calculated on the coldest day of the year (in case of heating) when heating equipment capacity needs to cover high heating need which can be lowered with efficient HRU, while throughout the year conditions are not so extreme and then HRU efficiency is not as influential. It must be noted that sensitivity analysis can be performed only for numerical variables; for example, the window type needs to be described by its two variables, U-value and g-value (solar transmittance). Both of these window properties have a major effect on energy efficiency, hence, neglecting one of them would result in poor sensitivity analysis. On the other hand, including both window variables in the analysis separately, as is shown in this example, creates combinations of window properties which do not have a real world equivalent. There is also the option of combining the sensitivities of the properties (U-value and g-value) of the type variable into one variable (window type) which should be considered and tested. For that reason, it is currently best to view those variables separately (U-value and g-value), but with caution when choosing an optimal design solution [30].

6. THE PILOT PROJECT FOR THE ADVANCED ENERGY ANALYSIS METHOD

Figure 14 Alppila high school building located in Helsinki, Finland [31]

The pilot building for this work was Alppila high school (Alppilan lukio) building located in Helsinki, Finland. The school was built in 1957 and has four sections with an interior courtyard in the middle. Besides teaching spaces, the building has a gymnasium, a ball room and a kitchen. The building is particular from an architectural point of view as it was built partly on a rock and the building’s height and profile follow the shape of the rock slope. Alppila school is attended by approximately 750 students.

The building needs to be retrofitted in a way that complies with the current Finnish building regulations. They state that a school building needs to have mechanical ventilation capable of providing a minimum fresh air requirement (3 $l/s \cdot m^2$). As this building was built in the late 1950’s, most spaces have only exhaust ventilation, with a very low airflow rate. Several spaces (kitchen, gymnasium and ball room) have mechanical ventilation, but without a heat recovery unit. The building’s heating source is Helsinki’s district heating network.

Retrofitting the building with a modern ventilation system would increase indoor air quality, but would at the same time also increase energy consumption. Therefore, the focus in this work was placed on lowering the energy consumption on the heating demand side while minimizing retrofit costs. The goal of the retrofit was for the building to have primary energy consumption not exceeding 130 kWh/m^2 annually, which would place the building in the B energy class (by Finnish regulations for educational buildings).

The work was done in two stages, firstly with little information available on the building, which matches level 200 of the Level of Detail (LOD) classification. For that simpler model, retrofit options were analyzed and an optimal option was selected. The following task was to collect detailed information about the building and to create a model which matches the LOD 300 classification, and to select an optimal retrofit option. The selected retrofit options from both models were compared, along with their life cost calculations.

6.1. LOD 200 BES model

6.1.1. Geometry model

At the beginning of the project, not much information on the building geometry was known. In older buildings 3D models are usually nonexistent, and 2D technical drawings, if they can be found, are often outdated. In this work, a free online mapping data source was used to acquire data about the building's footprint and orientation. Such sources could be Google Maps, Here Maps, OpenStreetMaps, etc. In this work, Google Maps was chosen as a data source. Using a mapping service as a source of data in an early phase of a retrofit project enables the modeler to quickly simulate entire districts or complexes of buildings, before focusing on a single building.

SketchUp 3D modeling software was used to extract data from Google Maps, as it contains a geo-location module for importing Google Maps data. Unfortunately, when using SketchUp, the user cannot define thermal zones in a 3D model (at least without a plug-in for the BES software), needed as an input to BES software , Therefore, only the 2D footprint was created in SketchUp and then exported to MagiCAD to create floors and define spaces.

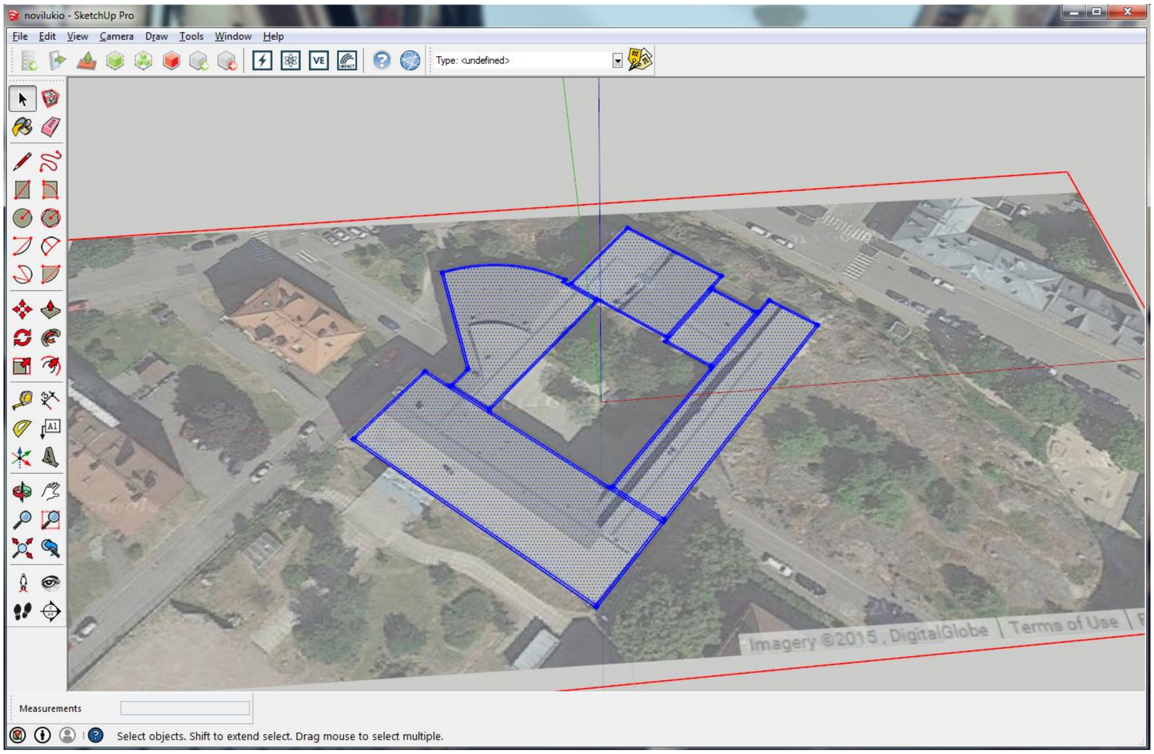


Figure 15 Creating the footprint of the school building in SketchUp with the data from Google Maps

In Figure 15 the SketchUp interface is presented with the created footprint of the building, with footprint dimensions and the building orientation obtained from Google Maps. The building’s footprint was created manually on the top of Google Maps satellite data that captured only the roof of the building which can be a source of high uncertainty. However, the precision was not of high importance in this phase of the project since the BES was based on an LOD 200 model, which requires only the approximate size and shape of a building. After the building footprint was created, it was exported to MagiCAD using the .dwg file. In MagiCAD, floors and spaces were created and then exported as an IFC file for later use in energy simulation applications.

The building massing was very problematic for this phase as it was built on a rock slope, so different parts of the building had a different number of floors, and the floor height varied. Once again, Google Maps with its Street View service was used as a tool that helps create floors. Using Street View enables the modeler to observe the number of floors (at least those above ground layer) and the shape of the building from its sides without visiting the building location.

Figure 16 Google Street View representation of Alppila school building; Street View shows how the building profile is influenced by the shape of the rock slope

In Figure 16, the southeast side of Alppila school building is presented with its profile influenced by the rock slope, but without dimensional data. The height of the floor, the size of each floor (as it is influenced by shape of the rock slope) and height of the floor, which is partly underground, were estimated using typical floor heights, maps and Street View services. Since the information about the floor plan of the building was still unknown was, each floor of specific parts of the building was created as one space, as shown in Figure 17. Although the window area is one of the crucial parameters in energy analysis, that information was missing in this phase. However, it was possible to add the glazing area later, as most of BES applications include the feature that enables automatic window area creation, done later in the modeling process.

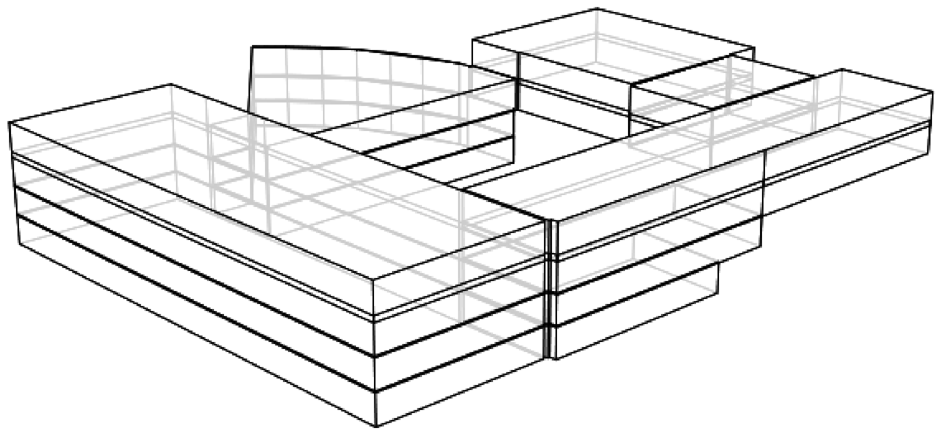


Figure 17 View of the created IFC simplified (LOD 200) building model, with approximate size, shape and without glazing

6.1.2. The building energy simulation model

The BES software used in this work was RIUSKA, based on the DOE-2.1E simulation engine. In RIUSKA, the Alppila school building LOD 200 model was imported through the IFC import module. The IFC file contained not only the geometry and spaces of the building, but also the construction types (the external wall, the ground floor, the roof, the internal slab, etc.), which needed to be populated with their thermal properties. The thermal properties of the envelope elements at this phase were not yet identified, so they were assumed. The assumption values (default values) were based on the Finnish building regulations [32] by building type and year of construction. In Table 4, the default U-values are presented, which are valid for a Finnish building built before 1969.

Table 4 Default U-values for a Finnish building built before 1969 [32]

Construction element	U-value (W/m^2 K)
External wall	0,81
Ground floor	0,47
Roof	0,47
Door	2,20
Window	2,80

While building regulations contain only the U-values of a specific construction type used in the building, energy simulations usually need much more data, such as information about the construction layers of walls, roofs and floors, or the glazing properties of windows. However, in this phase with high uncertainty of other input variables, information about the exact properties of building's thermal mass and the transmittance of windows was not essential. In this case in particular, the typical building elements were constructed with the help of engineers who had many years of experience in energy analysis of buildings throughout Finland. The following is a description of typical construction elements used in this case (the material is sorted from inside to outside):

- External wall: concrete layer (80 mm thickness), polystyrene (40 mm thickness), concrete layer (70 mm thickness)
- Ground floor: surface material (2,5 mm), concrete (100 mm), polystyrene (75 mm)
- Roof: steel sheet (6 mm), air gap (50-100 mm), wood (90 mm), plastering (20 mm), fiber board (115 mm), concrete (160 mm)

A typical window installed before 1969 was a double glazed window with total solar transmittance of 70 % and U-value of 2,8 W/m^2 K.

The window area was still unknown in this phase and the estimated range of window areas was added in a parameterized simulation. Range was estimated by the observation of the building's façade. The airflow rate range was estimated using experience from other projects since the building regulations contain typical ventilation rates that are valid only for new buildings. The building infiltration rate (n_{50}) was found in the building regulations, and it is 6 1/h for buildings in Finland built before 1969. BES software RIUSKA allows for the direct input of n_{50} infiltration values, which are then converted to infiltration rates for the atmospheric pressure.

The ventilation system was created as an exhaust ventilation system that extracts indoor air, which is replaced with fresh air drawn through the inlets for outdoor air. Information about spaces with mechanical supply ventilation were not yet available. Finnish building regulations give the typical Specific Fan Power (SFP) for buildings with exhaust ventilation for buildings built before 2012, which is 1,5 kW/m^3/s. SFP is a variable which is not constant for a given fan, but it depends on the amount of air circulated through the fan and the electrical power used by the fan to produce the needed circulation. The electrical power of the fan further depends on its efficiency and total pressure loss in the ventilation system. Since in this work only SFP was taken into account, fan efficiency and total pressure loss were adjusted in a way to form SFP of 1,5 kW/m^3/s. Additionally, SFP was also set to 2 kW/m^3/s to analyze the effect it has on energy consumption. The ventilation schedule was obtained from the City of Helsinki's energy calculation values and amounted to 1710h (work days 7-16 h, closed during school holidays).

Heating system uses the energy from Helsinki's district heating network, while the heating elements are radiators. According to the regulations, the efficiency of the heating distribution system varies from 0,80 to 0,90,depending on a radiator temperature mode and on pipe insulation. Both of these variables were still unknown in this phase. The auxiliary power of the heating system was also taken from regulations, as 2 kWh/m^2 annually.

Domestic hot water (DHW) energy consumption was estimated to be 11 kWh/m^2, (heated from 10 to 55° C) with transmission efficiency of 0,89 and exploitable heat losses of 50 %, all from the building regulations.

Interior thermal loads were also estimated using the building regulations and are presented in Table 5**.** The schedules for interior loads were obtained from the City of Helsinki's energy calculation values. For schools, it amounted to 1520 hours annually (work days 8-16 h, closed during school vacations) with the utilization rate of 75%. Since school buildings have a highly predictive schedule, no other schedule was considered in this work.

Table 5 Internal thermal load for a typical school building in Finland [33]

Load type	Thermal load (W/m^2)
Lighting	18
Equipment	8
People	14 (~0,19 persons/m^2)

The indoor heating set point temperature was set to 21°C according to the Finnish standard. The selected weather file for the simulation was Helsinki's typical metrological year (TMY), version 2012.

The building energy simulation model that was created matched the LOD200 model description, with estimated size, shape and other properties, but without glazing surfaces. Next step was to assess the impact of different possible estimations on energy consumption, perform sensitivity analysis and choose the case that is closest to the actual building.

Although it was mentioned in chapter 5 that a range width of input variables has a high impact on sensitivity analysis, range could only be estimated in this phase. More accurate sensitivity analysis could be achieved by using probability distribution of building elements and materials in a given building era, if one existed. Up until that point, the energy analyst's skills and experience is the only tool available for estimating possible range of input values.

Table 6 gives a summary of variables used as inputs to the simulation, and values that are probable for a school building built at the end of 1950s in Finland. The default type is the type found in Finnish building regulations. Window types were not included in this analysis, because the windows on the building are very typical for that age and their properties were described beforehand.

Table 6 Input values for a parameterized simulation

Variable name	Variable value/range
External wall type	• concrete + mineral wool (0,31 W/m^2 K) • brick + concrete + mineral wool (0,54 W/m^2 K) • fiber board + mineral wool + concrete + brick (0,46 W/m^2 K) • default wall (0,81 W/m^2 K)
Ground floor type	• reinforced concrete + polystyrene + fiber board (0,16 W/m^2 K) • default ground floor (0,47 W/m^2 K) • reinforced concrete + fiber board (0,57 W/m^2 K) • reinforced concrete + bitumen (0,72 W/m^2 K)
Roof type	• steel sheet + air gap + fiber board + concrete (0,33 W/m^2 K) • default roof (0,47 W/m^2 K)
Window area per space area	10 – 25% (with steps of 5) [1]
Equipment thermal load	0 – 10 W/m^2 (with steps of 2)[2]
Lighting thermal load	5 – 20 W/m^2 (with steps of 5)[2]
Indoor airflow	1,2 – 1,5– 2 dm^3/(s m^2)[2]
Infiltration (n_{50})	3 – 6 1/h (with steps of 0,5)[2]
SFP	1,5 – 2 kW/m^3/s
Heating system distribution efficiency	0,8 – 0,9

[1] Source for selected range was based on experience and observation of the building façade while also accounting for values from the building regulations [32]

[2] Source for selected range was based on experience from other projects while also accounting for values from the building regulations [32]

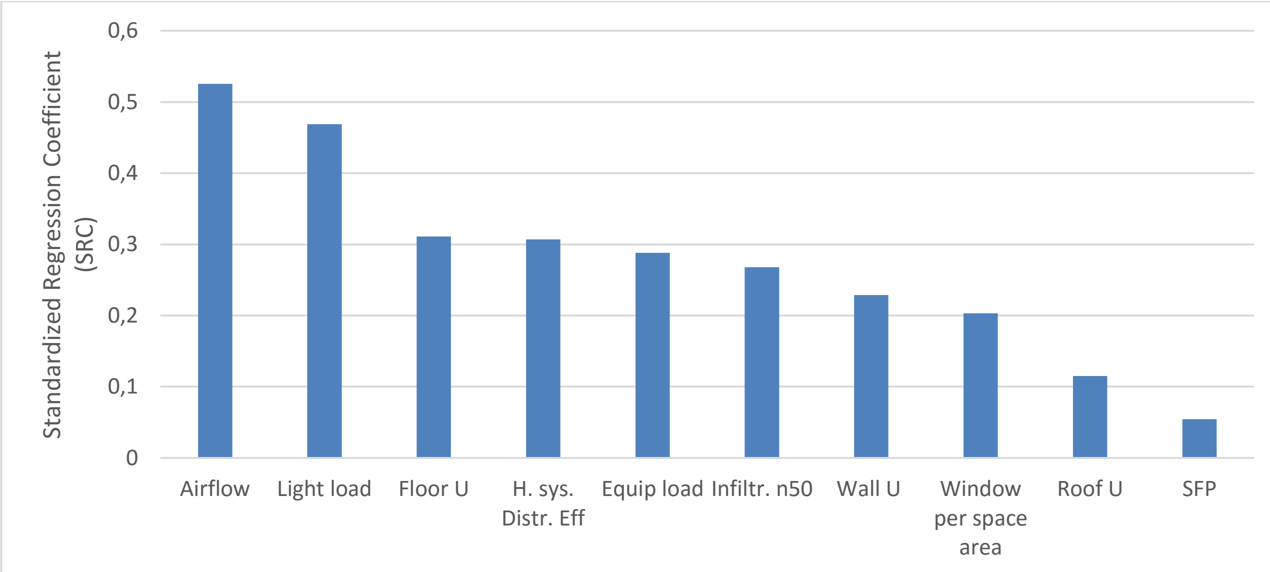


Figure 18 Visualization of the results from the sensitivity analysis for the KPI primary energy as support for the data collection process

There were 258048 possible combinations of the listed input variables, from which 1000 random combinations were simulated, and the sensitivity analysis was performed from the obtained results. Figure 18 provides a visualization of the effect which a specific variable has on the primary energy consumption of the school building. In other words, it gives an indication of how extensively an incorrect estimation can influence the building consumption and points to the possibility of using variables default values. Figure 18 ranks variables by their influence and shows their SRC values which indicate variable importance. In this specific energy model, airflow rate estimation has the highest impact on consumption, followed by the light load estimation, as well as the floor U-value and the heating system distribution efficiency. The equipment load, infiltration value, external wall U-value and window per floor space ratio estimation have a lower, but still significant impact. The roof U-value and SFP estimations have a small influence on the simulated consumption, hence, default values could be used for these variables.

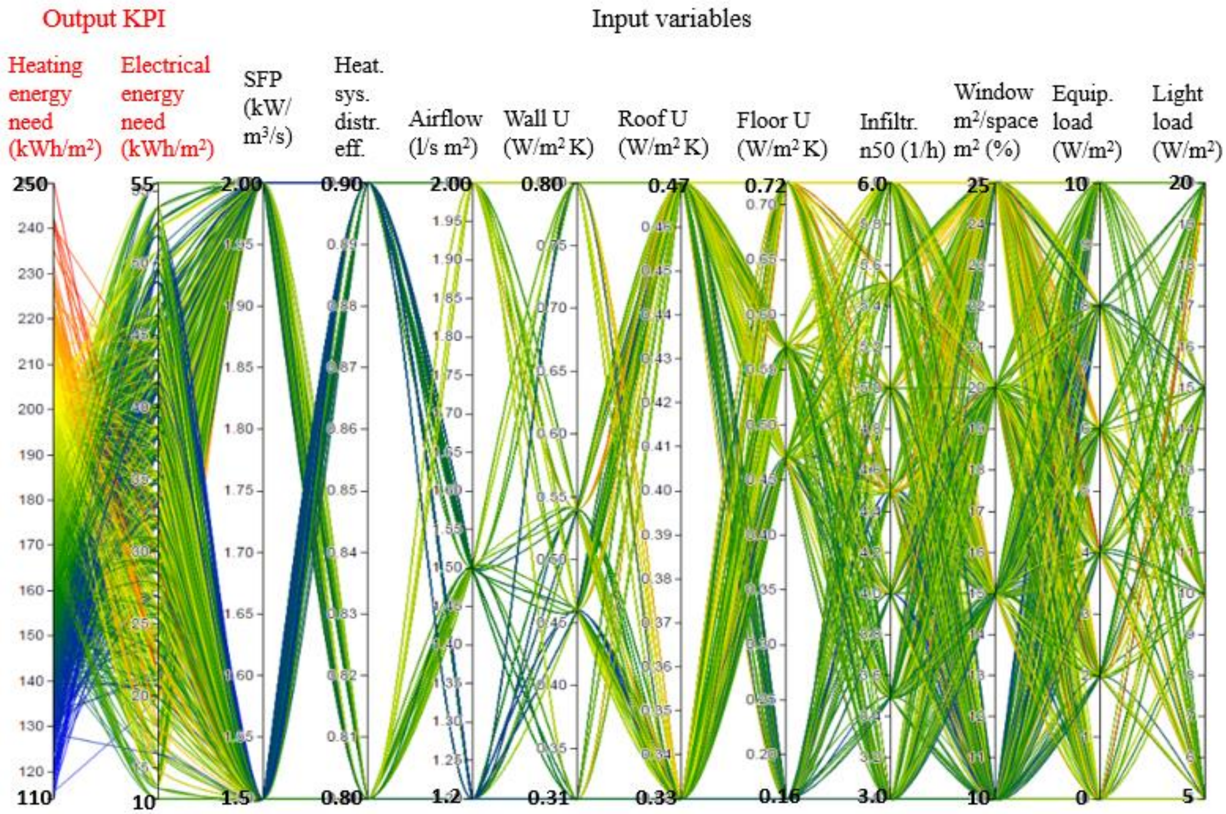


Figure 19 Visualization of energy simulation inputs and results for 1000 cases

In Figure 19, the results from 1000 energy simulations are visualized with different combinations of input values using a web application developed by Finnish company Granlund. Each line represents one simulation case and displays input values and output KPI values, while the color range goes from blue (lower value) to red (higher value) depending on selected KPI (in this case heating energy need). This web application enables one to filter the results by selecting the range of each variable. The cases of interest would be displayed in colors, while the dismissed cases would be displayed in gray. This enables the analyst to quickly filter out unfitting simulation cases during the additional data collection phase.

The output simulation variables show that the calculated heating energy need varies from 110 to 250 kWh/m^2, while electrical energy need varies from 10 to 55 kWh/m^2. Input variables for each case can also be read from the visualization.

Since the results suggest relatively large range of possible KPIs (heating and electrical energy needs in this case), it was necessary to perform a better estimate of input variables. Using the available building drawings, it was possible to estimate the window/space area ratio more precisely, and set it to 15% (10 – 25% in the previous analysis). The design airflow rates were also specified in building's documentation as 1,6 l/(s·m²) per room(on average). During a site visit, the light load and equipment load were estimated to 15 W/m^2 and 4 – 6 W/m^2 respectively.

In the drawings and during the site visit several different external wall types were discovered, but their exact thermal properties and position on the building was still unknown. However, their discovery made it easier to narrow down the average U-value for the external wall to somewhere between 0,4 and 0,6 W/m^2 K. Furthermore, the default value of 0,47 W/m^2 K was used for the roof, as the sensitivity analysis showed a small impact of the roof structure. The floor U-value was narrowed down to the range 0,45 – 0,60 W/m^2 K after examining the construction layers in drawings. Furthermore, as the heating system distribution showed a significant impact on energy need, after additional data collection, efficiency was assumed to be around 0,90 (for 70/40°C radiator temperature mode and insulated pipes). After this filtering, only one simulation case remained (Figure 20) and it was used as a base case for the comparison of different retrofit options.

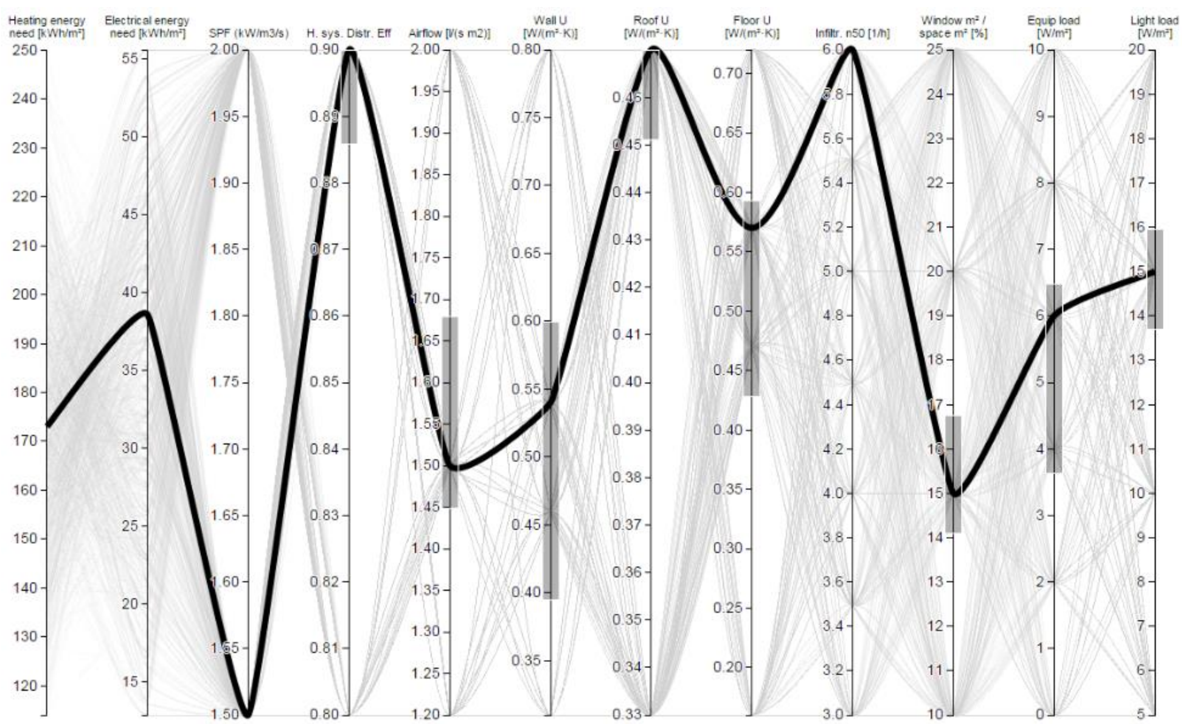


Figure 20 The selected LOD 200 simulation case after filtering out the other 999 cases using more accurate input parameters

This procedure has shown how it is possible, with estimated values and additional brief data collection, to narrow down from many possible cases to one case which is the best representation of the actual building so far. All relevant input and KPI (output) variables for the selected LOD 200 case are presented in Table 7.

Table 7 Input and output values for selected LOD200 case

Simulation input variables	Value	KPI (output) variables	Value
Airflow [l/(s·m²)]	1,5	Heating energy need [kWh/m²]	173
Wall U [W/(m²·K)]	0,54	Electrical energy need [kWh/m²]	38,6
Roof U [W/(m²·K)]	0,47	Primary energy (E-value) [kWh/m²]	187
Floor U [W/(m²·K)]	0,57	Building envelope heat loss [W/m²]	38,8
Infiltr, n50 [1/h]	6	Heating space max [W/m²]	120,9
Window m² / space m² [%]	15	Heating total max [W/m²]	120,9
Equip load [W/m²]	6		
Light load [W/m²]	15		
SFP [kW/m³/s]	1,5		
Heating sys. distribution eff. [%]	90		

It is important to note that at the time of creating the LOD200 model it was assumed that the entire building had only exhaust ventilation, but it was found on the drawings that the gymnasium, the dining hall and the ballroom had both mechanical supply and exhaust ventilation. Given that these systems do not have a heat recovery unit (HRU) and that the air is preheated using the same heating source, this does not affect heat the energy consumption, but it affects the electricity consumption from fans, which was ignored at this stage.

6.1.3. Selecting the optimal retrofit of the LOD 200 building model

Finding a building retrofit solution for a simple, LOD 200 model was done by using the BES software RIUSKA's parameterized simulation with random sampling, and the final selection of an optimal solution was done through a life cost calculation (LCC).

The main goal of Alppila school's retrofit was to meet the current indoor air quality requirements, determined as the minimum of 3 l/(s·m²) of fresh air for an educational building. Due to this requirement the main parameters of the ventilation system were set and could not be optimized. The selection of HRU unit was the only parameter that could be varied, but as explained later in the text, a HRU type depends on specific space requirements (indoor air quality and fire safety). For this reason only one HRU unit was selected for every case in LOD 200 simulations- a rotating heat exchanger, which is the most common HRU used in Finland nowadays. The SFP value was set according to current Finnish standards for supply air, as 2 kW/m^3/s.

The infiltration value (n_{50}) for new windows was lowered to 4 1/h (estimation), and in cases where the old windows remained, the infiltration was left unchanged (6 1/h).

The impact of the added insulation was analyzed by adding extra layers of mineral wool to the existing walls, floors and roof surfaces, as can be seen in Table 8. This method was convenient as it was easy to calculate the costs associated with the addition of extra insulation layers. Two types of windows that are usually used in the existing buildings were also included in the analysis.

Table 8 Input variables for a parameterized simulation of the LOD 200 model

Variable name	Variable value/range
External wall type	• Default: brick + concrete with mineral wool (50 mm) (0,54 W/m^2 K) • EW1: default with 100 mm mineral wool (0,33 W/m^{2}K) • EW2: default with 150 mm min. wool (0,23 W/m^{2}K) • EW3: default with 200 mm min. wool (0,17 W/m^{2}K) • EW4: default with 250 mm min. wool (0,14 W/m^{2}K) • EW5: default with 300 mm min wool (0,12 W/m^{2}K)
Ground floor type	• Default: reinforced concrete + fiber board (120 mm)(0,57 W/m^{2}K) • GF1: concrete with 50 mm mineral wool (0,49 W/m^{2}K) • GF2: concrete with 100 mm mineral wool (0,30 W/m^{2}K) • GF3: concrete with 150 mm min. wool (0,21 W/m^{2}K)

	• GF4: concrete with 200 mm min. wool (0,16 W/m^{2}K) • GF5: concrete with 250 mm min. wool (0,13 W/m^{2}K)
Roof type	• Default :steel sheet + air gap + concrete with fiber board (0,47 W/m^{2}K) • R1: default with 50 mm mineral wool (0,41 W/m^{2}K) • R2: default with 100 mm mineral wool (0,26 W/m^{2}K) • R3: default with 150 mm mineral wool (0,19 W/m^{2}K) • R4: default with 200 mm mineral wool (0,15 W/m^{2}K) • R5: default with 250 mm mineral wool (0,13 W/m^{2}K)
Window type	• Default 2 glass layer window (2,8 W/m^2 K and total transmittance 70%) • 3 layered glass window with argon between them (6 mm thick glass, 2 clear, 1 glass low-e) (1 W/ m^2 K and total transmittance 50%) • Fenestra Primus MSE Super 3 layered (0,82 W/ m^2 K and total transmittance 38,4 %)
Infiltration (n_{50})	4 1/h for new windows, 6 l/h for old windows (default)

It was immediately clear from the results that the windows needed to be retrofitted, or else, the goal of a maximum 130 kWh/m^2 primary energy consumption was not going to be met. After the calculation of 200 random samples of possible 432 combinations and after discarding the results above 130 kWh/m^2 primary energy, 126 simulation cases were left for an LCC analysis.

6.1.3.1. The Life Cost Calculation of an LOD 200 model

Simulation input and output variables of 126 cases were exported to Excel to select an optimal retrofit solution. The output variables (KPIs) that were important for this analysis were primary energy, heating energy and electrical energy consumption. The primary energy was only used to filter out the results higher than 130 kWh/m^2, while heating and electrical energy were used to calculate the consumption costs. The price for district heating energy in Helsinki was taken as 0,0488 €/kWh and the price of electrical energy with transfer costs was 0,09 €/kWh.

Investment costs for retrofitting windows and insulating envelope structure were other cost variables besides energy cost in this analysis. In the following table the price of a 2,5 m^2 window with its installation costs is given.

Table 9 Window installation costs in EUR for a window size of 2,5 m^2

Demolition of old window	Window 1 W/m^2 K	Window 0,82 W/m^2 K	Installation	Connection with wall	Window sill	Jamb moulding
100	320	432	55	82	26	92

To facilitate the process, the price was brought to the 1 m^2 level and it amounted to 128 €/m^2 for a window with U-value of 1 W/m^2 K and 173 €/m^2 for a window with U-value of 0,82 W/m^2 K. For the envelope structure retrofit, two costs considered in this analysis were the costs of the insulating material and the labor costs. The source of cost information was the internal Granlund's documents and the final values were approximated for different insulation thicknesses. The price used in the calculation for a 100 mm thick mineral wool was 6 €/m^2 and 38 € for 1 man-hour. In Table 10 prices for different insulation thicknesses are listed and in Table 11 the LOD 200 model surface areas of different envelope structures are listed.

Table 10 Installation costs of insulation for different thicknesses

Min. wool thickness (mm)	Material cost (€/m^2)	Man-hour (p/h)	Total cost (€/m^2)
50	3	0,1	6,8
100	6	0,1	9,8
150	9	0,2	16,6
200	12	0,2	19,6

250	15	0,3	26,4
300	18	0,3	29,4

Table 11 Surface area of envelope structure types for the LOD 200 model

Envelope structure	Area (m^2)
Wall	3228
Roof	2955
Floor	3597
Window	1373
Total building, LOD 200	9163
Total building, real	7529

The LCC analysis was done using the prices from Tables 9 and 10 by multiplying them with the area from Table 11, depending on the simulation case input variables. For all 126 simulation cases, the investment costs were calculated and presented “per square meter” (real building area), because of the differences in building area between LOD 200 and 300 models.

Future costs, such as heating and electrical energy consumption needed to be discounted before they could be compared with the current costs, because of the ‘Time Value of Money’. Time Value of Money is the idea that the money available at the present time is worth more than the same amount in the future due to its potential earning capacity. The time value of money results from two factors:

- Inflation, which is erosion to the value of money over time
- Opportunity cost: for cash or existing capital, opportunity cost is equivalent to the benefit the cash could have achieved had it been spent differently or invested [34]

Future costs are converted to present value (PV) with the following equation:

$$PV_Y = \frac{F_Y}{(1+DISC)^Y} \qquad [4]$$

Where F is the value in the future, $DISC$ is the discount rate and Y is the number of years in the future. The value in the future for this analysis was the energy consumption cost, the discount rate was the real interest rate without the inflation (in Finland it is 4%) and the number of years in the future was 25 (the usual case for LCC in Finland). Possible rises in energy price, future maintenance and service costs were not analyzed in this work.

In Table 12 ten cases with the smallest payback time and the base case are presented, together with energy consumption and costs. The chart in Figure 21 presents ten retrofit cases and the base case with their cumulative costs (brought to the present value) throughout a period of 25 years. The chart shows that, sometime between year 11 and year 12, all retrofit cases return their investment cost. As these cases were based on many approximated input variables, the final decision on selecting the optimal case was not done in this phase. However, the LOD 200 BES model analysis showed that there was reasonable payback time on retrofits assessed here and that the owner should seriously consider retrofitting the building and invest in a more detailed data collection and analysis beforehand, which will be covered in the next subchapter.

Table 12 10 LOD 200 simulation cases with the smallest payback time and base case (yellow)

Case	Window U [W/m²·K]	Wall U [W/m²·K]	Roof U [W/m²·K]	Floor U [W/m²·K]	Heating en. need [kWh/m²]	El.en. need [kWh/m²]	Tot.energ. cost [€/m²a]	Invest.cost [€/m²]	LCC [€/m²]
Base	2,8	0,54	0,47	0,57	173	38,6	11,92	0	186,2
1	1	0,33	0,26	0,3	69,9	45	7,46	36,1	152,63
2	1	0,54	0,15	0,3	72,8	45	7,60	35,7	154,49
3	1	0,54	0,26	0,2	74,6	45	7,69	35,1	155,26
4	1	0,33	0,19	0,3	66,6	45	7,30	38,7	152,78
5	1	0,23	0,47	0,3	75,8	45	7,75	35,1	156,20
6	1	0,17	0,47	0,3	73,7	45	7,65	36,4	155,88
7	1	0,17	0,26	0,6	75,8	45	7,75	35,6	156,65
8	1	0,33	0,47	0,2	76,4	45	7,78	35,5	156,99
9	1	0,33	0,26	0,16	64,7	45	7,21	40,8	153,35
10	1	0,23	0,19	0,6	74,6	45	7,69	37,0	157,12

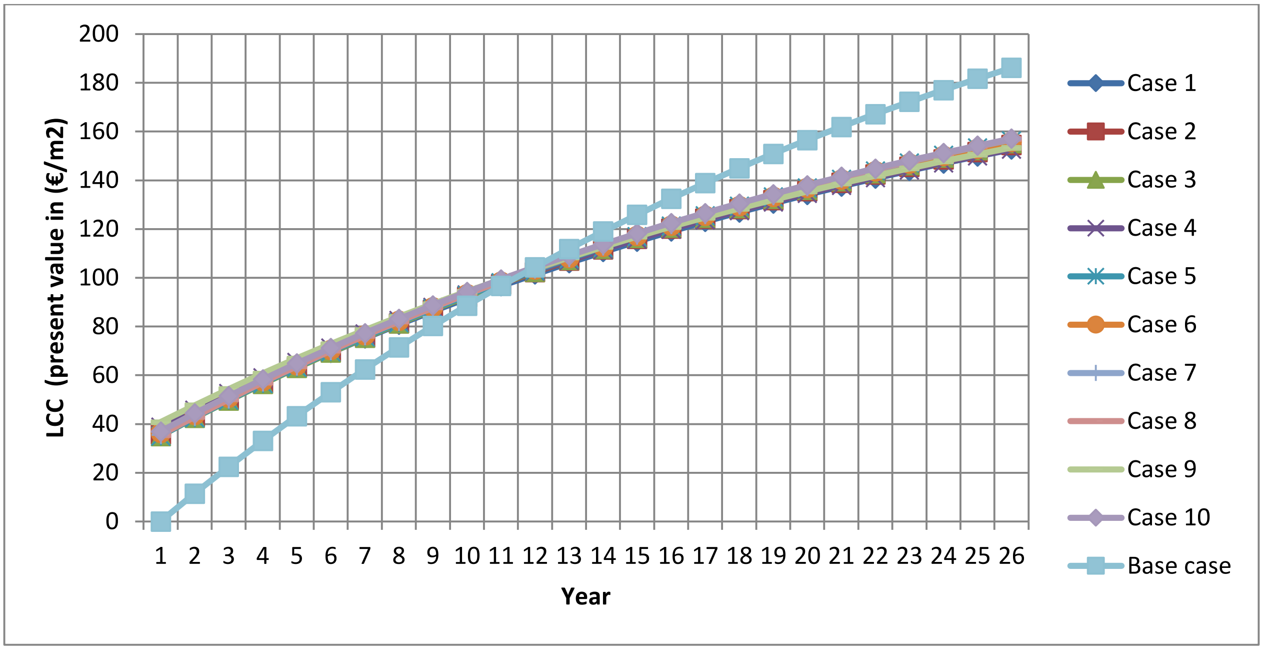


Figure 21 Chart with cumulative costs in present value for ten potential LOD 200 retrofit cases compared to the base case

6.2. The LOD 300 building energy simulation model

6.2.1. Geometry model

The data collection process in Alppila school has resulted in the collection of old and new architectural drawings from which a more accurate geometry model was created, corresponding to the LOD 300 classification.

Architectural drawings were imported to the MagiCAD software where spaces were created in the similar way as in the LOD 200 model. The differences here was that it was possible to create spaces which corresponded to the actual rooms in the building and assign windows with right dimensions, which gave actual window per space ratio. Created spaces added internal walls which resulted with an additional thermal mass in the model, which was not available in the LOD 200 model.

Creating a 3D geometry model from a more accurate source of information was particularly beneficial in this case, as the building's profile followed the shape of the rock slope, which means that different floors in different parts of the building were of a different height and space area (Figure 22). The floor height varied from 2,20 m to 3,60 m depending on the part of the building and the floor. It was also possible to model the zero floor more accurate, as it was partially underground, and not possible to see in the photographs.

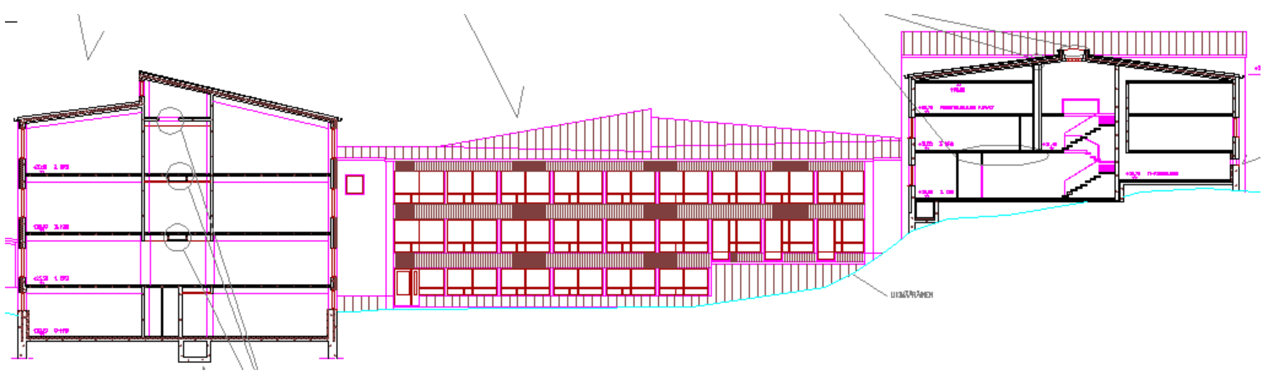


Figure 22 Cross-section of Alppila school building which shows the roof pitch, different floor heights and how the rock slope affects the building shape

The roof of the school building has a small pitch (Figure 22) and since most of the energy simulation software have problems modeling pitched surfaces, a simplification was made. The roof was created as a flat roof but on a greater height, in between the highest and the lowest point of the roof. The volume of the space under the roof, therefore, remained the same as in the actual building.

6.2.2. Building energy simulation model

The IFC file containing the building's geometry and element types (windows, external and internal walls and slabs, ground floor, roof and spaces) was imported into RIUSKA so that thermal, indoor air and HVAC system properties could be defined.

Then, a building inspection was done during which the elements of the building envelope were assessed by drilling holes, inspecting layers, measuring material moisture and performing a microbe analysis. For the purpose of this work, only the thermal properties of the envelope from the inspection were used.

As a result of the inspection, and with the help of old construction drawings, different envelope construction types were identified, as listed in Table 13. The types are listed along with their name (attributed in the building inspection) and belonging U-value. The internal surface U-values are not listed since the heat flow between rooms was not important for this analysis, but their thermal properties have been included in the model. Two listed roof types, have same thermal properties, so only one was used as input to BES.

Table 13 Building envelope construction properties

External wall	• Non-load bearing wall with a sheet metal surface (0,31 $W/m^2 \cdot K$) • Load bearing gable wall with Siporex (0,62 $W/m^2 \cdot K$) • Ground-facing wall of the basement spaces (0,25 $W/m^2 \cdot K$) • Ground-facing gable wall (0,59 $W/m^2 \cdot K$) • Gymnasium wall (0,57 $W/m^2 \cdot K$) • B- section courtyard side wall (0,69 $W/m^2 \cdot K$) • Tojax wall (0,23 $W/m^2 \cdot K$)
Ground floor	• Non-insulated ground-facing wall (0,83 $W/m^2 \cdot K$) • Crawl space floor (0,16 $W/m^2 \cdot K$)

	• Machine room floor (0,81 W/m²·K) • Gymnasium floor (0,53 W/m²·K) • Styrofoam insulated wall (0,22 W/m²·K)
Roof	• Pitched roof (0,47 W/m²·K) • Flat roof (0,47 W/m²·K)
Internal wall	• Brick internal wall • Load bearing internal wall • Ballroom internal wall
Internal slab	• General internal slab • Gymnasium and ballroom slab
Window	• Double layered window with clear glass (2,8 W/m²·K)

Some walls of the building are partly underground and partially above ground. These walls were assigned the category of non-underground floors if they contained windows (a wall cannot be underground if it has a window). Walls that have surfaces mostly underground, and do not have window surfaces, have been defined as ground-facing walls.

The indoor air quality and HVAC system related parameters were acquired from the old HVAC system drawings. The heating energy source is district heating, and the space heating element are radiators with a temperature regime 70/40°C. Based on the given temperature regime, and the fact that the pipes are insulated, a distribution system efficiency was set to 90%, according to the regulations [32]. Some of the heating energy is used to pre-heat the supply for the gymnasium, ballroom and dining hall, while the rest of the building only has exhaust ventilation. There is no heat recovery for the supply ventilation in the existing building. SFP values were taken from the regulations and they are: 1,5 kW/m3/s for exhaust and 2,5 kW/m3/s for supply ventilation. The indoor airflow range varies from 0 to 9,6 l/(s·m²), depending on the space type. In Table 14 airflow rates are presented for typical spaces, and are constant.

Table 14 Typical airflow rates for typical spaces in Alppila school

Space type	Airflow rate l/(s·m²)
Classroom	1,2
Gymnasium	5
Ballroom	5
Kitchen	9,6
Dining hall	2,2
Toilet	1,6
Hallway	0

The interior thermal load data has been partly collected in the inspection, and partly estimated as:

- Equipment load: 3,5 W/m^2
- Lighting load 14 W/m^2
- People load 0,187 p/m^2

For the analysis of domestic hot water (DHW) consumption, the average monthly values from the measured historical values of water consumption were used as input to RIUSKA. For the consumption of drinking water data from Figure 23 were used, representing the volume of water that was going to be heated (from 10 to 55°C) and assuming the transmission efficiency of 0,89 and 50% of usable heat losses. The calculated average for the yearly energy consumption for domestic water heating equals to 5,3 kWh/m^2. This is partly an estimate, as not all of the consumed water is DHW. However, the use of the calculated value is more accurate than the use of the building regulation value, stated as 11 kWh/m^2 default for a school building.

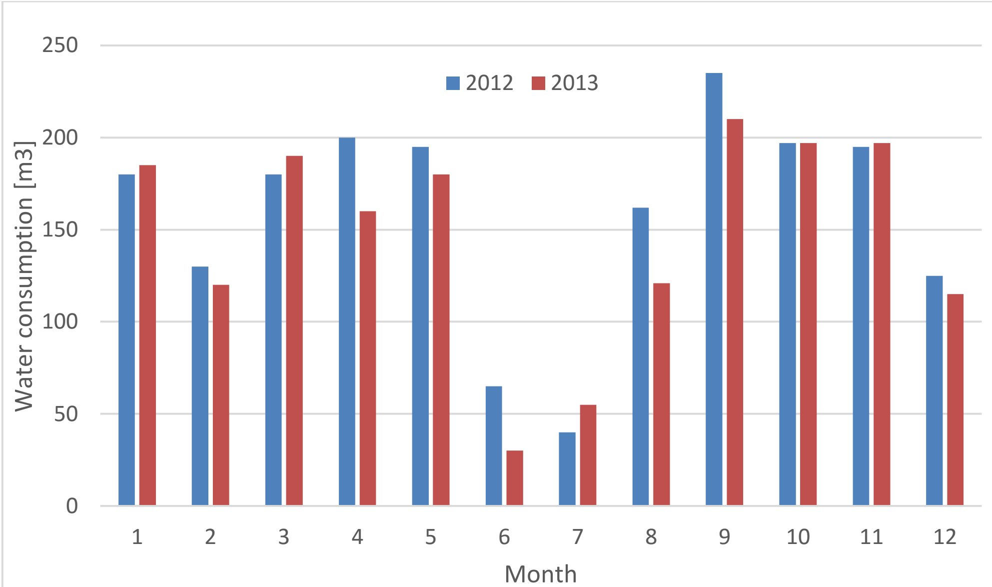
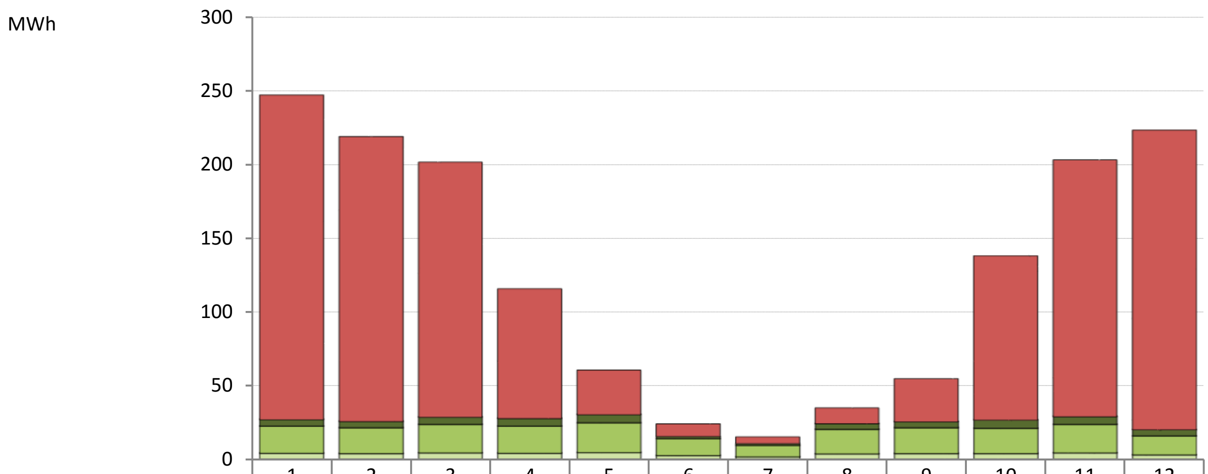


Figure 23 Monthly water consumption for the period from 2012 to 2013 for Alppila school building

After the input of the updated building data, energy simulations were iteratively calculated with an adjustment in the infiltration rate (as it is difficult to obtain) until the energy need was near the energy consumption values acquired from utility bills. The simulation results for the annual energy need are given in Table 15**,** and the monthly results are presented in Figure 24.

Table 15 Annual energy need of the LOD 300 building model

Type of energy need	MWh	kWh/m^2
Heating energy	1246	164,7
Electric energy	294	38,9
HVAC electricity	53	7
Lighting electricity	194	25,7
Equipment electricity	47	6,2



	1	2	3	4	5	6	7	8	9	10	11	12
Heating energy	220	193	173	88	30	9	5	11	29	112	174	203
HVAC, other electricity	5	5	5	5	6	1	1	4	4	6	6	4
Lighting electricity	18	17	19	18	20	12	8	16	17	17	19	13
Equipment electricity	4	4	5	4	5	3	2	4	4	4	5	3

Figure 24 Monthly energy need for the LOD 300 model of Alppila school building

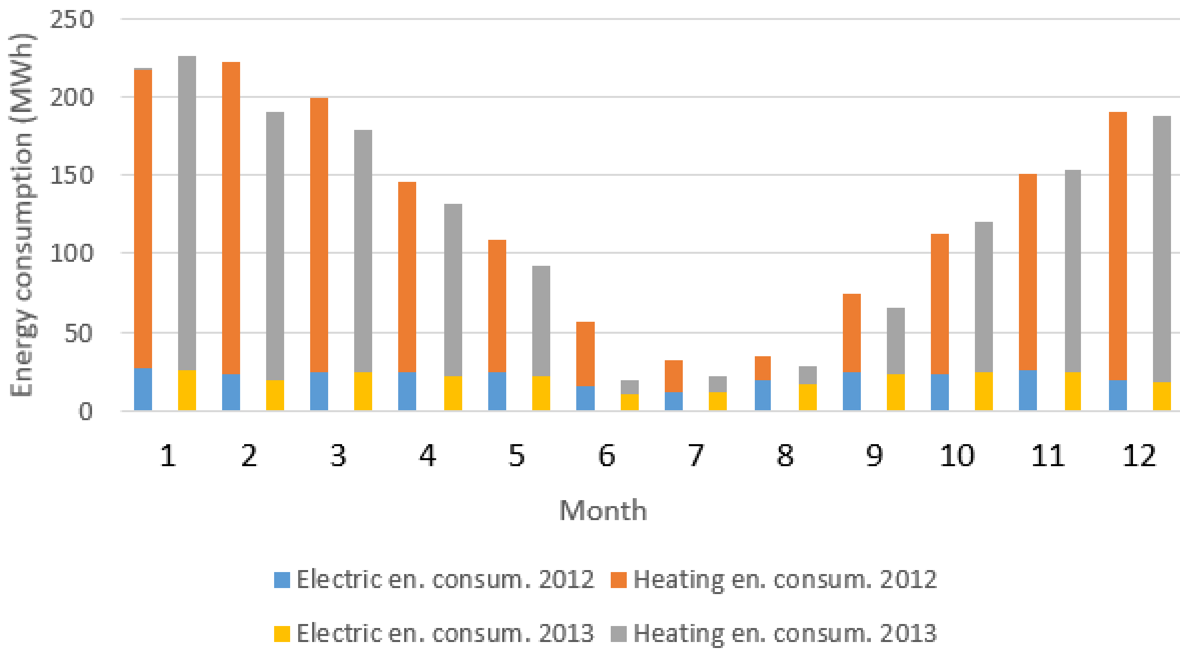


Figure 25 Monthly energy consumption during 2012 and 2013 from utility bills

Comparison between Figure 24 and Figure 25 presents the same pattern of energy consumption between simulated model and consumption from 2012 and 2013 utility bills. The comparison of consumption per space area as in Table 16 shows a slight difference in heating energy consumption. There could be many reasons for this difference, such as: the previously mentioned DHW consumption estimation, a different infiltration rate, a difference between the statistical weather data and the actual weather, differences in the real and 3D model geometry and many more. It is important ensure that this BES model adequately represents the actual building, so the differences in consumption (between the as-is model and the retrofitted model) can be compared.

Table 16 Comparison between the measured (from utility bills) and the simulated output values

	Measured values (kWh/m^{2}a)	Simulated values (kWh/m^{2}a)
Heating energy consumption	159	164,7
Electrical energy consumption	37	38,9

6.2.3. Selecting the optimal retrofit of the LOD 300 building model

After the LOD 300 BES model has been verified, possible retrofit solutions were simulated, and the optimal solution was selected using the LCC. The ventilation system was created to satisfy the project goals, which is to ensure that the system would supply fresh air to the school building and to satisfy the Finnish building regulation D3 [33]. According to the regulation, the minimum allowed fresh air airflow is 3 l/(s·m^2). The ventilation system was calculated as a constant volume system, with the SFP value of 2 kW/m^3/s, which is according to current regulations. In Table 17, all ventilation groups are presented, together with their operating schedules and heat recovery unit (HRU) characteristics. Typical operating hours for a school in Helsinki were used as schedules for the comparison of retrofit cases. However, it is possible that the ventilation system in the ballroom, the gymnasium and the kitchen would be turned off while those facilities are not in use, (exact schedule is currently unknown). Heat recovery unit (HRU) characteristics listed in Table 17, include the design, annual energy efficiency and minimal allowed waste air temperature. HRU types and corresponding design efficiencies were taken from the RIUSKA library. The annual energy efficiency of the HRU unit was calculated in RIUSKA using the yearly weather data and taking into consideration the minimal allowed temperature of waste air for a specific HRU type (freezing protection). Different ventilation groups have different HRU types because of the different air quality requirements and fire safety standards. Considering the fact that rotating heat exchangers have certain leakage between fresh and waste air, they should not be used for toilets or for a kitchen. Instead, a cross plate heat exchanger and a hydronic heat exchanger are considered for the toilet and the kitchen respectively. Despite its lower efficiency, a hydronic heat exchanger was used in kitchen due to its higher fire resistance relative to the cross plate heat exchanger, which is important for a kitchen exhaust system.

Table 17 Ventilation groups and their characteristics

Ventilation group	Schedule	HRU type	HRU energy efficiency in design conditions	Calculated annual energy efficiency	Waste air min allowed temp.
Ballroom	Work days (7-16) – school holidays (1710 h/a)	Rotating heat exchanger	80 %	66 %	-8°C
Gymnasium	Work days (7-16) – school holidays (1710 h/a)	Rotating heat exchanger	80%	66 %	-8°C
Kitchen	Work days (7-16) – school holidays (1710 h/a)	Hydronic heat exchanger	50 %	46 %	0°C
Toilets	Work days (7-16) – school holidays (1710 h/a)	Cross plate heat exchanger	60 %	52 %	-2°C
Other spaces (mostly classrooms)	Work days (7-16) – school holidays (1710 h/a)	Rotating heat exchanger	80 %	64 %	-8°C

6.2.3.1. The Life Cost Calculation of the LOD 300 model

The selection of the optimal retrofit solution was done in the same way as with the simple model (LOD 200); the first batch of simulations with 200 different combination of input parameters with the existing window type and higher infiltration (4,5 1/h) was performed, followed by second batch of 200 simulations, but with changed window types and lower infiltration (3 1/h). The results from the first batch of simulations have shown that the windows need to be retrofitted if the energy consumption goal is to be met; therefore the cases with old windows have not been included in the LCC analysis.

The costs of the windows, insulation and their installation are the same as described in 6.1.3.1, the difference being the surface areas of the envelope elements and total building floor area, which are given in Table 18. For the LCC analysis, investment costs were divided by the actual building's area, not by the model area. It is important to note that the BES software RIUSKA can only define one construction type per envelope structure when performing multiple parameterized simulations. For example, in this case, every existing external wall type was replaced with a weighted average wall (0,46 W/m²·K), and the same applies to floor types, which were replaced with a weighted average floor (0,44 W/m²·K).

Table 18 The surface area of envelope structure types for the LOD 300 model

Envelope structure	Area (m^2)
Wall	3483
Roof	2819
Floor	2739
Window	1411
Total building, LOD 300	7566
Total building, real	7529

In Table 19, ten different LOD300 simulation cases with the smallest payback time are presented. The simulation results suggest that the optimal window for each one of the presented cases was a 3-layered glass window with the U-value of 1 W/(m²·K). Also, for most cases, the element that should not be retrofitted was the floor. The cumulative cost (in present value) through a 25 year time period is shown in Figure 26 for the base case and ten retrofitted cases. The point in which the base case line and the retrofit case line intersect is the time of payback for a specific retrofit. It can be seen that all cases presented in Figure 26 have a similar payback period of approximately 11 years and. Hence in order to make a decision about the best retrofit one should take into account opinions from other stakeholders (owner, architect, contractor, etc.).

Table 19 LOD 300 base case and simulation cases with the smallest payback time and (yellow)

Case	Window U [W/m²·K]	Wall U [W/m²·K]	Roof U [W/m²·K]	Floor U [W/m²·K]	Heating en. need [kWh/m²]	El.en. need [kWh/m²]	Tot.energ. cost [€/m²a]	Invest.cost [€/m²]	LCC [€/m²]
Base	2,8	0,46	0,47	0,44	164,7	38,9	11,54	0	180,3
1	1	0,46	0,15	0,44	83,9	38,8	7,59	31,2	149,7
2	1	0,46	0,15	0,3	78,6	38,8	7,33	34,7	149,2
3	1	0,33	0,19	0,44	79	38,8	7,35	34,6	149,3
4	1	0,17	0,26	0,44	74,2	38,8	7,11	36,5	147,7
5	1	0,33	0,15	0,44	76,9	38,8	7,24	35,7	148,9
6	1	0,46	0,26	0,16	79,6	38,8	7,38	34,6	149,9
7	1	0,23	0,47	0,44	87,9	38,8	7,78	31,5	153,1
8	1	0,17	0,47	0,44	85	38,8	7,64	32,9	152,2
9	1	0,46	0,47	0,16	90,4	38,8	7,90	31,0	154,4
10	1	0,33	0,47	0,3	88,1	38,8	7,79	31,9	153,6

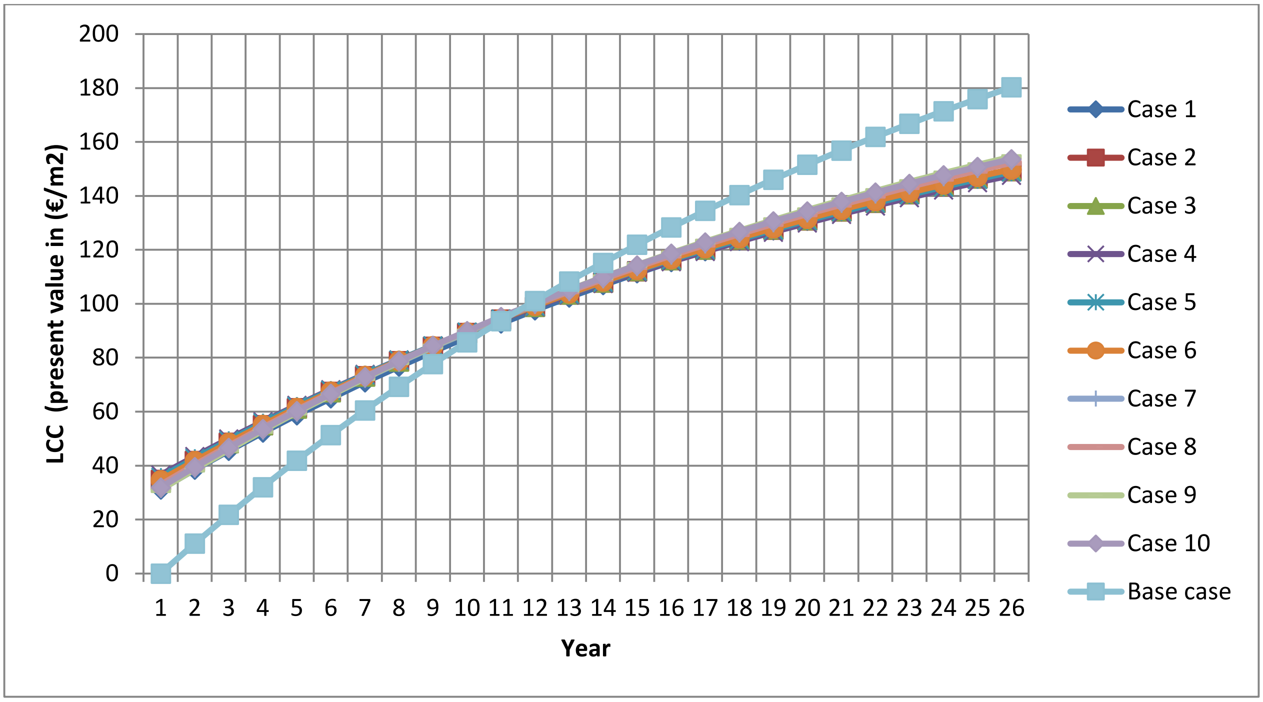


Figure 26 Cumulative costs in present value for ten potential LOD 300 retrofit cases compared to the base case

7. A COMPARISON OF TWO MODELS AND THEIR RESULTS

In this chapter, a summary of the two BES models that were created in this work is given. In Table 20, the input variables from both existing building BES models are summarized, including their sources, the typical values are values taken from Finnish building regulations [32], [33]. The primary discrepancy between the models is in their geometry, where the LOD 300 model had good accuracy (drawings) and the LOD 200 model was modeled using approximation, based on images from Google Maps and approximation of the building’s shape and height. There are also differences in envelope thermal properties, interior thermal load, type of ventilation system in certain spaces and in water consumption. The effect that those differences have on final results (energy needs) is somewhat decreased since the results are compared based on per-square-meter values.

The results shown in Table 21 suggest that the heating energy need results, electrical energy need results and the life cost calculation results are quite similar between the two analyzed models for building in existing state. This does not necessarily mean that the approximated model is as close in imitating the more accurate model, but in retrofit solution analysis presented in tables 12 and 19 and figures 21 and 26 give the impression that the models are approximate to each other regarding retrofit KPI’s, such as the LCC value and payback time. LOD 200 model came out with higher investment costs, but lower energy costs then LOD 300 model in retrofit solution selection, which decreased the differences between models, when looking at LCC values. Payback time, which is possibly the most important parameter for a decision making regarding the retrofit is around 11 years for both models. Furthermore, in both models, the cases with the quickest payback time have similar parameters, such as the same window type and preferring retrofit of walls and roof structures. The difference in retrofit measures is evident in the floor structures, where the results of the LOD 200 retrofit analysis have pointed to the recommended retrofitting of the floor for each case that was analyzed, and LOD 300 did not. This difference is most probably caused by the much larger floor area and higher U-value in the simpler model than in the LOD 300 model.

In Table 21, the simulated energy needs with the LCC value (for 25 years) for both models are listed.

Table 20 Comparison between existing building LOD 200 and LOD 300 input variables

	LOD 200 model		LOD 300 model	
Input variable	**Value**	**Source**	**Value**	**Source**
Geometry				
Model area [m^2]	9163	The footprint and the shape of the building were created using G. Maps, Streetview and photographs. Dimensions are approximate. Window area was acquired from drawings	7566	The geometry model was created using architectural drawings with actual dimensions and shape.
Model volume [m^3]	31230		28468	
Wall area [m^2]	3228		3483	
Roof area [m^2]	2955		2819	
Floor area [m^2]	3597		2739	
Window area [m^2]	1373		1411	
Window area per floor space area [%]	15		15	
Building envelope				
Ext. wall U-value [W/(m²•K)]	0,54	Approximation between typical envelope types for the building period.	0,46 (w. average) actual: 0,23 – 0,69	Documentation. The weighted average is calculated using values from 7 types of wall in this building
Roof U-value [W/(m²•K)]	0,47		0,47	Documentation.
Ground floor	0,57		0,44 (w. average)	Documentation.

U-value [W/(m²•K)]			actual: 0,16 – 0,83	The weighted average calculated using values from 5 types of wall in this building
Window type	Double window	From Streetview/ photographs, typical window used in the b. period	Double window	From drawings and audit, typical window
Window U-value [W/(m²•K)]	2,8		2,8	
Infiltration (n_{50}) [h^{-1}]	6	Approximation, typical values.	4,5	Approximation, fitting with measured consumption.
Interior thermal loads				
People [W/m^2] / [p/m^2]	14 / 0,187	Typical values.	14 / 0,187	Typical values.
Lighting [W/m^2]	15	Approximation from site visit and typical values.	14	Audit.
Equipment [W/m^2]	6		3,5	
Year schedule [h/a], load [%]	1520, 75	Typical values, city of Helsinki.	1520, 75	Typical values, Helsinki city.
Ventilation system				
System type	Mechanical exhaust system,	From brief information at the beginning of the	Gymnasium, ball room and kitchen have mechanical	Old building HVAC drawings.

	without HRU	project.	supply system most of building has only. Exhaust system and some spaces do not have mechanical ventilation. Without HRU	
Airflows [l/(s•m²)]	1,5	Approximation.	Depends on space, 0-9,6, w. average 1,6	
SFP [kW/m3/s]	1,5	Approximation, typical values.	2,5 – supply vent. 1,5 – exhaust vent.	Typical values.
Schedule [h/a]	1710	Typical values, Helsinki city.	1710	Typical values, Helsinki city.
Heating system				
Energy source	District heating	Documentation, known fact (typical in Helsinki).	District heating	Documentation, known fact (typical in Helsinki).
Distribution system and its efficiency [%]	Radiator 70/40°C, 90% pipes insulated	Approximation using typical systems and site visit.	Radiator 70/40°C, 90% pipes insulated	HVAC documentation.
Auxiliary power for heating distribution [W/m^2]	0,23	Typical values, building regulations.	0,23	Typical values, building regulations.

<table>
<tr><td colspan="5">Domestic hot water</td></tr>
<tr><td>Energy consumption [kWh/m^2]</td><td>11</td><td rowspan="3">Typical values, building regulations.</td><td>5,3</td><td>Assumed based on measured water consumption.</td></tr>
<tr><td>Transmission efficiency [%]</td><td>89</td><td>89</td><td rowspan="2">Typical values, building regulations.</td></tr>
<tr><td>Part of losses exploitable [%]</td><td>50</td><td>50</td></tr>
</table>

Table 21 Comparison of energy need and the LCC between LOD 200 and LOD 300 existing building models

Type of energy need	**LOD200**	**LOD300**
Heating energy [kWh/m^2]	173	164,7
Electric energy [kWh/m^2]	38,6	38,9
LCC [€/m^2]	186,2	180,3

8. CONCLUSION

In this work, a new approach to advanced energy analysis methods for optimal building retrofit design was given. This approach is focused on the utilization of building information modelling (BIM) in building retrofit projects, and the selection of an optimal retrofit solution among many different possible solutions, based on a life cost calculation.

A BIM-based approach for building retrofit from an energy analyst's point of view was given as an illustration, where an energy analysis would be performed from the beginning of a project. This would enable an early insight into cost effectiveness and energy savings that could potentially be achieved for a specific building. Once a decision on building retrofit was made, and a more accurate simulation model was created, the optimal retrofit solution could be selected by the stakeholders based on different KPIs (Key Performance Indicator), such as energy consumption and life cost calculation (LCC). Energy consumption would be calculated using a building energy simulation (BES), and cost related parameters using an LCC analysis for many possible retrofit solutions. Throughout the process, information should be shared through the BIM server which would increase collaboration between different stakeholders.

In this work, a practical example of this approach was given. A high school building located in Helsinki, Finland served as a pilot building for this approach. Two models of the school building were created with different levels of development (LOD): a simpler model based on estimations (LOD 200) and a more detailed model with accurate information (LOD 300).

The LOD 200 model geometry was created using data from Google Maps, while variables related to envelope thermal properties, indoor thermal loads, the HVAC system, etc. were either estimated, or taken from building regulations. This was supported with a sensitivity analysis which assessed the importance of missing information, and, based on that importance, more accurate data collection was performed, or default values were used. The sensitivity analysis used in this work was a regression method with results represented in the form of standardized regression coefficients (SRC). After the existing building LOD 200 model was created, more than 100 cases with different possible retrofit solutions were simulated, and the results of 10 retrofit solutions with the shortest payback time were presented. An LCC analysis was performed for a period of 25 years.

The LOD 300 BES model was created using more accurate sources of information, such as building architectural and HVAC drawings, as well as building audit reports. After verifying calculated consumptions with measured consumptions from the building, simulations were done with more than 100 different retrofit options. Based on the LCC analysis and the comparison with the existing building model, the optimal retrofit solutions were presented. The optimal solution for the building retrofit was not selected in this work, as many of the analyzed cases had similar payback time and the decision was left to other stakeholders.

Based on the comparison of the LCC analysis results between two models (LOD 200 and 300), similar payback time can be seen for both models. There were other similarities between the presented retrofit solutions. For example, windows that were suggested to be replaced with new windows, as well as the proposed window type, was recommended in both models. The differences between the models were more apparent when looking at recommended retrofits of other building envelope elements. However, the LOD 200 model should not be used for making decisions on the type of retrofit, but only as a guideline for costs and savings possible if a particular building undergoes retrofit.

In this work, an issue regarding geometry creation arose in the case of the simpler model. Even though Google Maps gave very valuable information on footprint size, shape and orientation, some elements, such as height of floors and shape of the building profile, needed to be estimated. Other input variables to the BES, such as thermal properties of the envelope, the HVAC system properties, schedules, etc. were also estimated to some extent. In other words, this method is partly subjective. If more cities had 3D digital representations of their buildings in a format such as CityGML, geometry modelling would be easier and more accurate. There should also be more information on typical envelope elements, the HVAC system and other variable properties depending on the decade of construction and building type. This way, the method could be more standardized, which means less prone to subjective errors and very quick to perform.

Future work should be done to include more details about the HVAC system into the analysis, and to develop a library containing the most common HVAC systems used, together with their properties. Additionally, this method should be further tested with other buildings and neighborhoods. A neighborhood energy simulation could give information on potential exploitation of synergies between groups of buildings, such as district heating, local energy generation and storage, heat island effect and more.

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APPENDICES

I. CD-R disc